GEORGIA INSTITUTE OF TECHNOLOGY — OFFICE OF CONTRACT ADMINISTRATION

PROJECT ADMINISTRATION DATA SHEET

[x] ORIGINAL [ ] REVISION NO. ______

Project No. E-26-616 GTRI/GIT DATE 6 /13 / 83

Project Director: Dr. G. G. Eichholz School/Lab Nuclear Engineering

Sponsor: U.S. Dept. of Energy, Idaho Operations Office

Type Agreement: Contract DE-AS07-83ID12449

Award Period: From 5/9/83 To 12/8/84 (Performance) ______ (Reports)

Sponsor Amount:

	This Change	Total to Date
Estimated:	$ 106,688	$ 106,688
Funded:	$ 106,688	$ 106,688

Cost Sharing Amount: $ None Cost Sharing No: N/A

Title: Evaluation and Design of Low-Level Disposal Sites

ADMINISTRATIVE DATA

OCA Contact William F. Brown Ext. 4820

1) Sponsor Technical Contact:

M. J. Barainca
U.S. Dept of Energy
Idaho Operations Office
550 Second Street
Idaho Falls, ID

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Jim Detwiller, R&D Contract Br., CMD
U.S. Dept. of Energy
Idaho Operations Office
550 Second Street
Idaho Falls, ID
(208) 526-0014

Defense Priority Rating: None Military Security Classification: None

(or) Company/Industrial Proprietary: ______

RESTRICTIONS

See Attached DOE Supplemental Information Sheet for Additional Requirements.

Travel: Foreign travel must have prior approval — Contact OCA in each case. Domestic travel requires sponsor approval where total will exceed greater of $500 or 125% of approved proposal budget category.

Equipment: Title vests with GIT; however none proposed.

COMMENTS:

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GEORGIA INSTITUTE OF TECHNOLOGY — OFFICE OF CONTRACT ADMINISTRATION

SPONSORED PROJECT TERMINATION/CLOSEOUT SHEET

Date 1/28/85

Project No. E-26-616

School/~~Lab~~ NE

Includes Subproject No.(s) N/A

Project Director(s) Dr. G. G. Eichholz GTRC / ~~GIT~~

Sponsor U.S. Dept. of Energy, Idaho Operations Office

Title Evaluation and Design of Low-Level Disposal Sites

Effective Completion Date: 12/8/84 (Performance) 12/8/84 (Reports)

Grant/Contract Closeout Actions Remaining:

- [ ] None
- [xx] Final Invoice or Final Fiscal Report
- [xx] Closing Documents
- [xx] Final Report of Inventions
- [xx] Govt. Property Inventory & Related Certificate
- [ ] Classified Material Certificate
- [ ] Other ____________

Continues Project No. ____________ Continued by Project No. ____________

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E-26-616

GEORGIA INSTITUTE OF TECHNOLOGY
ATLANTA, GEORGIA 30332

SCHOOL OF
NUCLEAR ENGINEERING

May 21, 1976

Mr. Roger L. Burkhart
Project Officer
Quality Assurance & Training Branch
Division of Training & Medical
Applications
Bureau of Radiological Health
Dept. of Health, Education, and Welfare
Rockville, Maryland 20852

Dear Roger:

Please find enclosed a compilation of all the tests and the two examinations that were given to our students on NIR. Also, find a listing of the grades and in the last column of the table is the final grade as determined by a formula and some arbitrary assumptions. You will note that I do not have grades for the examination on March 15 and quizzes on March 16 and 18 because they were returned to the students who were asked to grade their own papers and were permitted to keep them. In the last column I have indicated also the suggested letter grade for each student. In general I believe the students did well on the course. You will note I gave only two failures (F) (for Mr. Sunderman and Mr. Simons). In the latter case the failure resulted because only two papers were turned in to us. I'm afraid Sunderman has a weak background. I was surprised at the great spread in background and basic knowledge of the students. Those to whom I gave an A on the course did unusually well on tests and examinations and those with grades of F, D and C- (6 in all) in general had a weak background or did not take the course very seriously. For example, several of these did not know that sound waves are not electromagnetic radiations. For these latter students, a course pitched at a lower level would have been more useful to them while a little more mathematics and problem solving would have been in order for the A students. With this spectrum of students, however, I think problems involving any mathematics probably would have turned off completely the F, D and C- students. I will discuss this in more detail in my final evaluation of the course when I receive comments from all the professors.

Finally, if there were more demand for the course, it would be better to offer two courses on NIR (one at the Freshman level, the other at the Senior level). However, I doubt this is a practical solution and perhaps our compromise could not be improved upon very much.

Sincerely,

Karl Z. Morgan
Neely Professor and
Technical Project Coordinator

KZM:lsg
Enclosures

FINAL REPORT OF K. Z. MORGAN ON EVALUATION OF THE
TRIAL RUN COURSE ON NIR AT GEORGIA TECH
APRIL 8-19, 1976
UNDER BRH CONTRACT E-26-616.
May 28, 1976

Student Evaluations

I have continued my efforts to obtain evaluations of this course from all of the students, but only 14 of the 20 have provided us to the present time with their evaluations. With only a few exceptions, the comments we have received are rather similar and the late replies during the past three weeks have added little new information to what we already had. Therefore, I am assuming we may not hear from the other six students, that their observations and suggestions would not have been much different from those we have or change significantly our conclusions, and that I am justified in considering this my final evaluation of the course.

General Comments

I share the view of most of the students that this was a unique opportunity for them to hear some of our country's experts discuss various aspects of NIR. In general (and with one exception) the students were very complimentary, stating that the course was very beneficial and provided the kind of information needed for them to perform better their jobs. One letter just received today from a student, for example, states, "From this course, I obtained all that I expected of it. I wouldn't consider myself to be an expert in the field of NIR from taking this course; however, I now have a good basic background in this area, enabling me to study in detail specific areas presented in the course when the need arises in Kentucky." If we had accomplished this with all the students, I would feel very satisfied with the course because our objective was to provide this basic information such that the student can continue to build on his knowledge; yet we hoped none of the students would go away considering himself an expert in NIR.

It was apparent from the questions, quizzes, exams and student evaluations that we had students representing an extremely wide background of education, experience and, perhaps, knowledge. As one student put it, "I felt I was alternately snowed and insulted by the course level." I do not know of any satisfactory way to completely avoid this defect. Some ways of partly solving this problem with future courses would be:

1. Set more restrictions on accepting the students so that they all have about the same coefficient of intellectual absorption. Perhaps we could require that all students have had as a minimum a course in college freshman mathematics, general physics and general biology, but such a requirement might leave out those who would profit most from the course. The students who did not know that sonic radiations are not electromagnetic radiations surely are poorly prepared for a job as a surveyor in NIR as well as at a great disadvantage in taking this course.

2. Subdivide the course into:

    a. various levels (technician, college senior, graduate level, etc).

    b. subject areas such that one course treated only mechanical radiations (sound, ultrasound, infrasound), another only r.f., another only lasers, another ionizing radiations, etc. All the students had some background in ionizing radiation and some had familiarity with coherent radiations while others were experienced in radar or r.f. radiations.

Personally, I would not wish to subscribe either to 1. or 2. above because I think the general type course we offered with very few restrictions on student qualifications is preferable when it comes to meeting the needs.

I think the two week course covering all the subject areas included in this dry run course at Georgia Tech is preferable to several shorter courses; but I believe a real effort must be made to streamline the course and reduce the number of lecture hours each day. I observed that I was not the only person who got tired and sleepy in the afternoons--especially during those afternoons when there were no laboratories or tours.

There was too much redundancy in some of the lectures, especially since most of the lectures repeated some of the basic and fundamental information given to the students the first day of lectures.

All the lecturers made a real effort to avoid the use of mathematics and, perhaps, this was carried to the extreme. I think it would have been helpful if some mathematical problems had been assigned by each lecturer as homework to be turned in the next day. In order that this not consume too much time, all the homework papers could be graded and returned at the end of the course together with a compilation of all the correct solutions to the problems. These problems would avoid calculus and higher mathematics and would for the most part be similar to types of calculations and problem solving which the surveyor might be confronted with in the course of his job.

Most of the lecturers had some good lecture props such as slides, transparencies, and handout material. However, there was a wide variation in the judicious selection of this material. In some cases, additional slides and handout material would have improved the lecture, while in one case there were far too many slides, some of which added little to the subject of the lecture.

I think the night lectures serve a good purpose, although I know that at least one person objected to them. The quizzes and exams provided the student a check on what he needed to know and enabled us to evaluate better our lectures and the comprehension of the students.

The tours and laboratories are an essential part of the program, but both need to be better organized. Copies of the revised laboratory instructions are enclosed.

I think perhaps too much time was given to r.f. and coherent radiations. Perhaps some of this time could be reassigned to mechanical radiations and to UV, infrared and visible radiations. The time given the first day to basic and fundamental discussions about radiations was appropriate, but the repetition of these discussions in subsequent lectures should be reduced (not completely avoided).

The lectures on mechanical radiations were given out of order, i.e. before the lectures on UV, infrared and visible radiations, but I believe this is desirable so the lectures on this subject can precede the tours and laboratories related to mechanical radiations.

The student packet provided the student with a wealth of information which he can continue to use after he returns home. Some of the students indicated that they intend to read all this carefully after returning home. It would have been helpful if the lecturers had been more familiar with what material was included in the student packet, and a request had been made by them for the students each day to bring pertinent portions of the packet with them to class for reference during lectures. One important observation was made; namely, there is no substitute for a good professor who is experienced in lecturing at the undergraduate level and who is provided enough time to cover the assigned subject matter. In all cases the highlight lectures were given by professors who are experienced in undergraduate teaching.

Comments on Specific Lectures (by number)

1), 2) I think combining Orientation and Introduction into a single lecture was a good idea. It saved some much needed time.

3) I believe the material on the Production and Behavior of E&M Radiations which I provided should be given in this lecture, but it encompasses far too much for a single lecture. I believe the solution is to provide this information in the written lecture, but in the oral presentation attempt only to hit the high spots emphasizing the differences between ionizing and non-ionizing, coherent and non-coherent, and E&M vs mechanical radiations. Particular emphasis should be given in the oral presentation to the unique, observable characterisitcs of non-ionizing radiations such as standing waves, differences in the E and H vectors in the near field, etc.

4) This lecture on Basic Concepts of Coherent and Non-Coherent Radiation brought in too much history and detail on certain aspects of coherent radiation. I believe it should carefully define all the unique nomenclature and new terms such as pumping, population inversion, stimulated emission, etc. It should discuss the basic requirements for lasing, how lasing is accomplished, and provide a brief introductory description of the principal types of lasers.

5) This lecture on Interaction of Radiation with Matter should build on what was presented in lectures 3) and 4) with most of the time given to coherent radiation interactions with matter. This was one of about 20 highlight lectures.

6) This movie could be improved ad updated. It was selected for our use after several less suitable movies were rejected by our staff.

7) This lecture was an excellent presentation for graduate students, but for this course there was too much presentation of scientific results of various experiments rather than a summary of bioeffects. A discussion of each topic under 7) in the course outline would have been more useful to the student than the discussion of certain experiments. Much useful information on the effects of these radiations on the eye was presented, but our students probably found difficulty retaining information presented in the graduate level style. Some good handouts with drawings and summaries of effects of UV, infrared and visible radiations would have aided the student in retaining the information and cataloging it properly for future reference.

8) I thought this lecture on the Helium Laser was an interesting and well presented lecture—another highlight lecture.

9) I found this lecture on Mechanisms, Construction, Applications and Hazards of Lasers one of the most interesting and best organized lectures of the series. It gave the proper amount of theory and tied it to practical applications. It gave answers to many questions about active medium, pumping, feedback, Q-switching, dielectric mirrors, energy storage, etc. It also provided an understanding of the important characteristics of the solid state, the semiconductor diode and the dye lasers. This was a highlight of the course.

10) I felt a generous amount of time should be allocated to group discussions of laser hazards as found by State Inspectors. I believe too much of the time here was devoted to repetitious slides and detailed comments and not enough student exchange (give and take of student experiences) or discussions of hypothetical situations that might be faced by the NIR inspector. Perhaps a list of hypothetical cases could be presented and a round table discussion would evolve as the students and instructor indicate what is considered an

appropriate response to various situations in real life.

11), 12), 13) and 14) The laboratory instructions (for labs A, B, C and D) and work sheets need much improvement to provide more detailed guidance to the student. More emphasis should be directed toward the associated hazards. The BRH should provide an assortment of survey instruments that can be shipped to the organization (on loan) as it offers this course. The laboratory outlines have been rewritten and are enclosed. The night lab D was interesting and worthwhile, but was very difficult to operate at night over such great distances because of security requirements and various jurisdictional areas over which, of necessity, the experiment has to be conducted.

15) The tour to the VA hospital was very useful but involved logistic problems in scheduling and arranging for demonstrations of equipment to suit our convenience.

16), 18) Much useful information was provided on Ocular Hazards of Lasers in these lectures. The more important equations used in evaluating the ocular risk were given. This is a rather involved subject and I believe the only way to simplify this presentation might be to hand out to the students work sheets on which these detailed calculations are given and then the lecturer paraphrase this material in his oral presentation.

17) This lecture on Laser Hazards to the Skin provided tables and graphs and gave the student just what he needed on the subject. Different grades of erythema, spectral reflectance, irradiance, radiant exposure, action spectra, etc, were explained clearly. This was a highlight lecture.

19), 20) I was a bit disappointed with these sessions on Practical Problems of Protection from Laser Radiations. As with lecture 10), they tired out the student with excessive slides rather than taking up a series of practical hypothetical problems. They did, however, define some new terms and develop several useful equations of specular power, safe viewing power, etc.

21), 22) and 24) These lectures on Measurements and Calculations in Laser Technology were well organized and pitched at the proper level. There was some repetition of definition of terms, etc; but I felt this amount of review was helpful because the new terms introduced were placed into relation with those defined earlier. This was a highlight lecture.

23) This discussion on Instruments (including homemade types) and Measurements was well received. This lecture elicited some response from the students but not enough. It is too bad that the good and the bad features of all the commonly available laser survey instruments were not given or furnished in the handout material.

25) The Tutorial Session worked out well, but unfortunately two students asked most of the questions.

26) This night lecture on r.f. Inspection Surveys was interesting, but the lecturer wasted much time on irrelative discussions and showed too many slides, many of which gave redundant information. The useful information could have been presented in half the time.

27) This OSHA lecture provided much useful information on Classes of lasers, protective measures, areas of risk, etc. Unfortunately, I do not have a copy of this lecture except in draft form, which I am not at liberty to use. Since Dr. Gass was invited by the BRH to give this lecture, perhaps the BRH should procure a copy of this revised lecture. Dr. Gass said he wished to do some touching-up on the draft copy given me.

28), 29) This BRH video tape was well done and provided just the information needed by the students. It should be updated from time-to-time in the future.

30) Most of the students did well on this exam on lasers.

31), 32) These lectures on Types, Applications and Special Biological Problems with UV, visible and infrared radiations were a highlight of the course.

33), 34) and 35) These lectures on Measurements, Calculations, Standards, and Control Measures for UV, visible and infrared radiations were very informative and interesting. There was not enough time to cover all the material and there was very little discussion of standards. Perhaps much of the material could be given to the students as a handout lecture and this could be paraphrased in the oral presentation that hits just the main points of the lecture.

36), 37), 38), 39), 40), 41) and 42) These lectures on Mechanical Radiations were limited to sonic and ultrasonic radiation (no discussion of infrasonic) and were another highlight of the lecture series. The written lecture, which was reviewed in the oral presentation, provides a valuable student reference.

43) Laboratory E on Microwave Oven Surveys was well developed. The instruction sheet is now rewritten and presented in better form in the enclosure.

44) This laboratory F was a failure and gets the grade of F. We were unable to get together the equipment for this laboratory and the substitute discussion had little if any relation to NIR. This laboratory procedure has now been rewritten completely (see enclosure).

45) Laboratory G was most interesting, but it lasted late into the night and became rather tiring. Some parts of the demonstrations should be shortened. This laboratory procedure is now written-up in better form (enclosed).

46) This tour to DeKalb Hospital provided the opportunity to demonstrate ultrasonic diagnostic equipment. We found that even with very close working relations with hospitals (as we have at Georgia Tech), it is difficult to schedule tours because they upset the hospital routine. Perhaps to obviate

this difficulty some video tapes should be made showing a wide variety of medical applications of NIR. Such an effort, however, would be very time-consuming and expensive to do a good job.

47) This lecture on r.f. Fundamentals was another highlight lecture--just about perfect.

48), 49) These lectures on r.f. Properties of Materials, r.f. Devices and Components were well developed.

50), 51) These lectures on r.f. Properties of Biological Tissue, Systems and Sources were highlight lectures.

52) This lecturer failed to cover some of the items in the outline for this lecture. What the lect urer said and his demonstrations were useful but hopefully in the revision he will stick to the outline.

53), 54) These lectures on r.f. Biological Effects and Hazards were very interesting and informative. I had the feeling that the r.f. hazards were depreciated (underestimated) in this and other lectures that follow.

55) I found this Tutorial Session very effective and productive even though it was held at night. It elicited much student response.

56) This lecture on Methods for Protection against r.f. Hazards was another highlight lecture.

57) This panel discussion was interesting, but again there was too much lecture by the panelists and not enough feedback between the students and panelists.

58) Combined with lecture 49).

59), 60) Standards and the Panel discussion were combined effectively except for the fact that the Standards part got shortchanged.

61), 62) Most of the students did rather poorly on this examination. Six students did unusually well.

63) Course evaluation by the students is a <u>must</u>. I do not know how we can get these evaluations from all the students in the future unless upon registration each student makes a deposit of $50 which is returned only when the evaluation is received.

Georgia Institute of Technology
A UNIT OF THE UNIVERSITY SYSTEM OF GEORGIA
SCHOOL OF NUCLEAR ENGINEERING AND HEALTH PHYSICS
ATLANTA, GEORGIA 30332
(404) 894-3720

June 10, 1983

Mr. Michael J. Barainca
Radioactive Waste Technology Branch
U.S. Dept. of Energy
Idaho Operations Office
550 Second St.
Idaho Falls, ID 83401

First Monthly Progress Letter -
Project No. 07-83ID12449; Our Project No. E-26-616

Dear Mr. Barainca:

During the first month of the project's existence major effort was devoted to planning project activities and arranging for project staffing. In view of the late date of initiation, past the midpoint of our Spring Quarter, only one research assistant was taken on. Mr. M. F. Petelka, a Ph.D. candidate in health physics has started on the first stage of the project, a review of the literature in the three areas of concern, landfill design and drainage, leaching under cyclic conditions and unsaturated flow. Starting June 20 a larger complement will be available to start planning the design of a drained facility.

Yours sincerely,

Geoffrey G. Eichholz
Project Director

GGE/vw

cc: J. Detwiler (DOE-IOO)
R. L. Dodge (EG&G Idaho)
W. F. Brown (OCA)

E-26-616

Georgia Institute of Technology
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July 14, 1983

Mr. Michael J. Barainca
Radioactive Waste Technology Branch
U.S. Dept. of Energy
Idaho Operations Office
550 Second St.
Idaho Falls, ID 83401

Second Monthly Progress Letter
Project No. 07-83ID12449; Our Project No. E-26-616

Dear Mr. Barainca:

During the past month activities have begun on the three major tasks: completion of the literature review, conceptual design of a depository trench and studies on water retention and leaching under drained conditions.

Miss Bonnie Wright and Mr. J. H. Whang have joined the project and will focus on the laboratory aspects of the work. Short test columns have been set up to relate moisture content and conductivity and calibrated test are under way. Mr. Petelka has collected information on cap and lining designs, alternative drainage systems and engineering problems at existing sites.

We are attempting to find information on the durability of drainage systems, on the permeability of multilayer systems and on clogging of drains by silting effects and plant roots. Some information on plant root problems has been obtained recently from the Savannah River Plant.

It is anticipated that the literature search should be completed shortly and design will start on a small scale test bed.

Yours sincerely,

Geoffrey G. Eichholz
Project Director

GGE/vw

cc: J. Detwiler (DOE-IOO)
R. L. Dodge (EG&G Idaho)
W. F. Brown (OCA)

Georgia Institute of Technology
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August 10, 1983

Mr. Michael J. Barainca
Radioactive Waste Technology Branch
U.S. Dept. of Energy
Idaho Operations Office
550 Second St.
Idaho Falls, ID 83401

Third Monthly Progress Letter
Project No. 07-83ID12449; Our Project No. E-26-616

Dear Mr. Barainca:

Work has continued during the past month in the major areas of concern: literature review, conceptual design of the drained trench and a study of moisture measurement and retention in unsaturated sand.

We have found very little information on long-term performance of buried drainage systems. On the other hand it appears fairly simple to underlay the disposal trench with a gravel layer of sufficient capacity to store rainwater at a rate that matches the permeability of the underlying soil strata. For coarse gravel clogging will not be a problem, but trench wall stability will have to be tested to establish infiltration rates for erosion material into the gravel bed. At the proposed depth, plant roots are not considered a significant problem, but subsequent seepage will depend on the moisture profile in the underlying soil.

For this reason we are attempting to set up a series of standard moisture samples that can be correlated with electrical resistance measurements for various soil types. That should enable us to monitor saturation changes on standing with time, as well as recharging and discharge cycles.

We are also beginning to look at waste leaching conditions under such fluctuating moisture conditions. We have obtained a sample of drained demineralizer waste from TVA-Sequoyah as a first possible leach test sample. It planned to follow the draft ANSI leach test procedure as far as possible.

Yours sincerely,

Geoffrey G. Eichholz
Project Director

GGE/vw

cc: J. Detwiler (DOE-IOO)
R. L. Dodge (EG&G Idaho)
W. F. Brown (OCA)

Georgia Institute of Technology
A UNIT OF THE UNIVERSITY SYSTEM OF GEORGIA
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September 8, 1983

Mr. Michael J. Barainca
Radioactive Waste Technology Branch
U.S. Dept. of Energy
Idaho Operations Office
550 Second St.
Idaho Falls, ID 83401

Fourth Monthly Progress Letter
Project No. 07-83ID12449; Our Project No. E-26-616

Dear Mr. Barainca:

During the past month work has continued on conceptual trench design and on studies of unsaturated mositure conditions. Information on the latter is important to predict the expected leaching conditions of waste in the presence of residual, capillarity-limited moisture content in backfill soil. The waste sample of TVA-Sequoyah waste has been analyzed, but the specific activity may be too low for useful leaching tests.

In the column studies on unsaturated sand, data have been obtained to relate conductivity and moisture content. In addition two types of segmented columns are being tested to permit repetitive tests under various conditions of unsaturation.

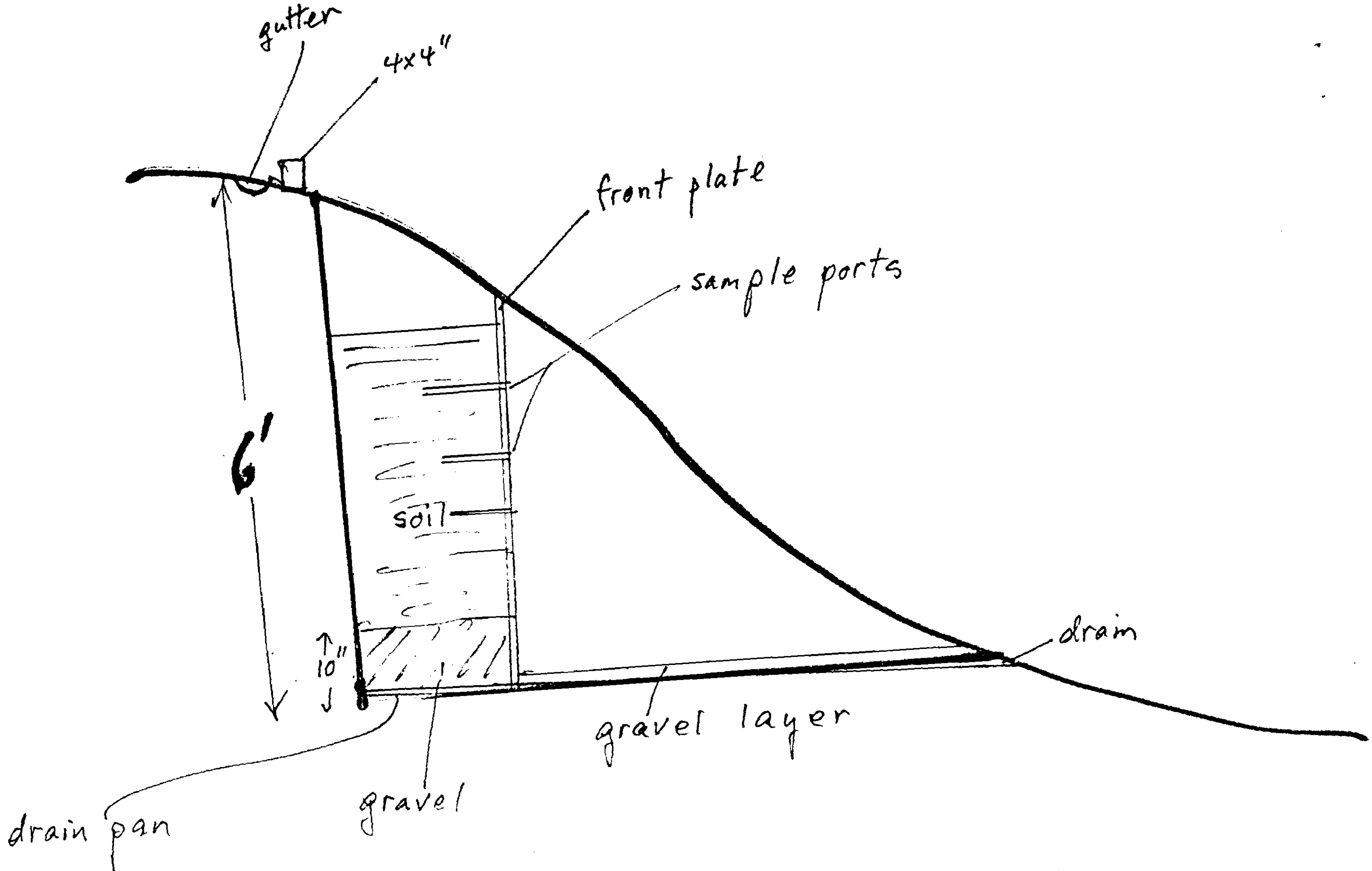
I attended the LLWMP Participants Meeting in Denver last week and briefly reviewed the status of the project with Mr. R. L. Dodge, the technical project officer.

Yours sincerely,

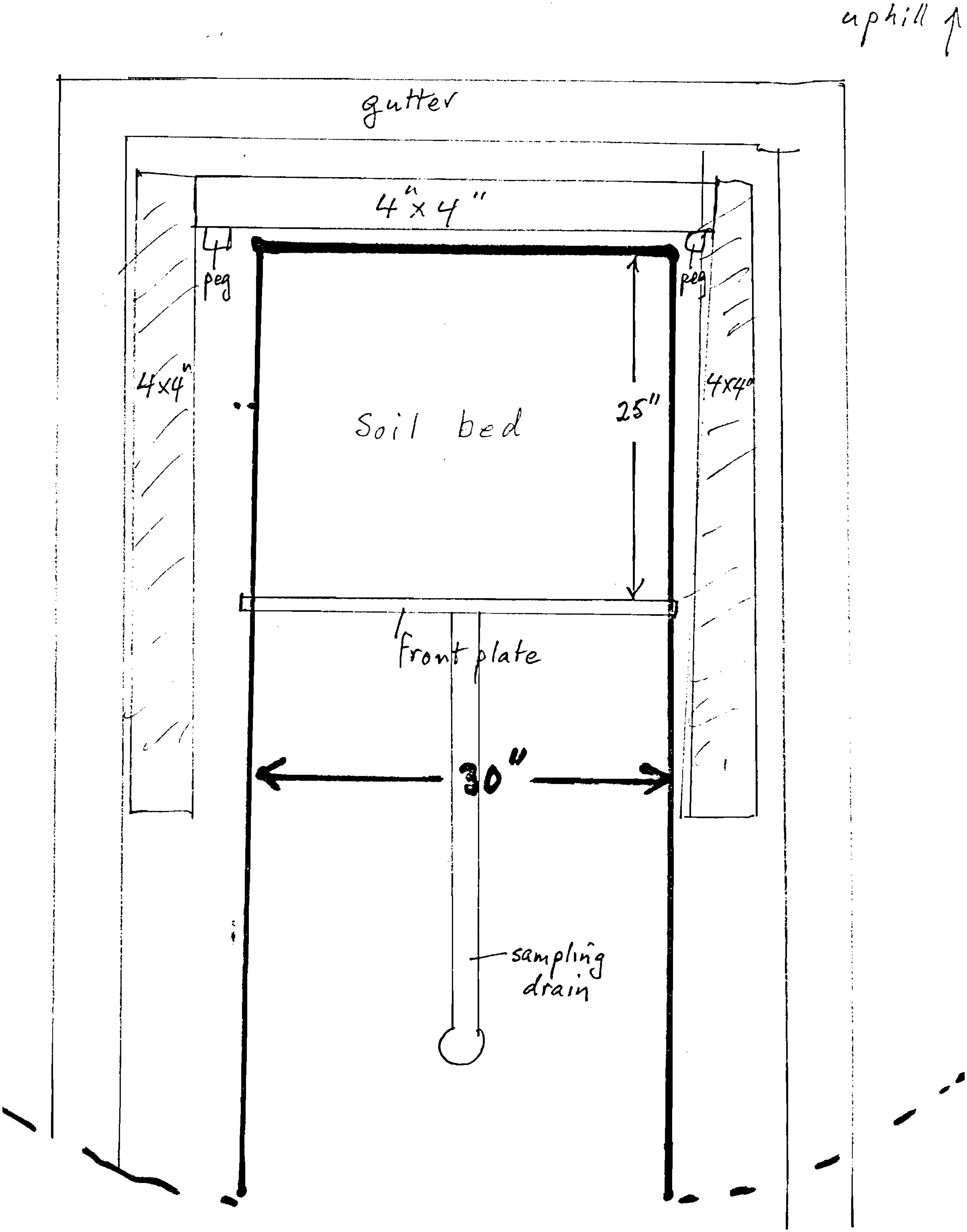
Geoffrey G. Eichholz
Project Director

GGE/vw

cc: J. Detwiler (DOE-IOO)
R. L. Dodge (EG&G Idaho)
W. F. Brown (OCA)



Trench Cross section



View of test trench

Georgia Institute of Technology
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November 11, 1983

Mr. Michael J. Barainca
Radioactive Waste Technology Branch
U.S. Department of Energy
Idaho Operations Office
550 Second Street
Idaho Falls, ID 83401

Sixth Monthly Progress Letter
Project No. 07-83ID12449; Our Project No. E-26-616

Dear Mr. Barainca:

Considerable progress has been made in developing the test bed, shown at two different stages in the attached pictures. An excavated trench has been lined, reinforced and graded and installation of a drain and test well positions is in progress. We expect to set up a shallow bed initially to test the rate of drainage and sample collection. We are also in the process of selecting a tensiometer system and calibrating it.

Work is continuing on leach tests on the Sequoyah waste resin samples. Circulating loops have been set up to pump soil-equilibrated water through the test samples. Four different waters are being used and samples will be drawn off at weekly intervals for analysis. It is expected that this will be a protracted experiment, in view of the low level of activity in the waste.

Tests on moisture determinations in sand samples have continued to correlate electrical conductivity measurements with moisture content. Eight columns were set up initially saturated with water. Four of them were allowed to drain gravitationally; four others were drained partially by suction. Conductivity data were obtained down to a one-percent moisture content. The conductivity - moisture plots were S-shaped with the main change occurring in the 35-80% range. Additional tests on four saturated columns indicated a slow change in conductivity with time. This is being studied at the moment and may be due to the movement of dissolved air. Further tests are planned for the coming weeks on sand columns in different particle size ranges and on samples of the soil being used in the main test bed.

Another set of tests is being started to investigate potential clogging of the gravel layer by silt being washed out from the waste bed. These tests are expected to be underway in the next two weeks; after that periodic sampling for silt deposits on the bottom of the test container and in a flow-through filter will be done over an extended period.

Yours sincerely,

Geoffrey G. Eichholz
Project Director

GGE/ctm
Attachment

cc: J. Detwiler (DOE-IOO)
R. L. Dodge (EG&G Idaho)
W. F. Brown (OCA)

LIBRARY DOES NOT HAVE Seventh Monthly Progress Letter

F18-6A

C H Rodgers

E-26-616

Georgia Institute of Technology
A UNIT OF THE UNIVERSITY SYSTEM OF GEORGIA
SCHOOL OF NUCLEAR ENGINEERING AND HEALTH PHYSICS
ATLANTA, GEORGIA 30332

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January 11, 1984

Mr. Michael J. Barainca
Radioactive Waste Technology Branch
U.S. Department of Energy
Idaho Operations Office
550 Second Street
Idaoh Falls, ID 83401

Eighth Monthly Progress Letter
Project No. 07-83ID12449; Our Project No. E-26-616

Dear Mr. Barainca:

The long Christmas break and the cold weather outside necessarily curtailed activities during the reporting period. However, with the new quarter renewed activities are taking place. Miss Bonny A. Wright has left the project on completion of her MSHP degree; Mrs. Denise D. Hardy, also a graduate student in Health Physics, has replaced her.

Drainage tests in columns filled with six different screen sizes of sand have been completed to demonstrate the residual moisture retention. Similar tests are being started on other soil types. Leach tests on TVA wastes have been started, but have not yielded any positive results so far.

Test work on the outside test bed will be resumed next week, primarily to explore drainage rates and to test and install new tensiometers.

Yours sincerely,

Geoffrey G. Eichholz
Project Director

GGE/cm

cc: J. Detwiler (DOE-IOO)
R. L. Dodge (EG&G Idaho)
W. F. Brown (OCA)

Georgia Institute of Technology
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February 8, 1984

Mr. Michael J. Barainca
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Idaho Operations Office
550 Second Street
Idaho Falls, ID 83401

Ninth Monthly Progress Letter
Project No. 07-831D12449; Our Project No. E-26-616

Dear Mr. Barainca:

The freezing weather still slows down work on the outside test bed. However, the system has been considerably overhauled during the past month to overcome structural problems. The bottom support of the base plate and drain has been reinforced and improved and the trench walls have been stabilized. As soon as the weather warms up here in the sunny South we expect to test the soil for moisture retention. We will also attempt to obtain a water balance for the bed. The tensiometers have been tested and we plan to correlate their readings with electrical conductivity tests for easier monitoring.

Multiple drainage tests on small sand columns have indicated that, for sand, residual moisture levels seem to be independent of pore size. Parallel tests are now underway with soils of varying sand/clay characteristics.

Leach tests on TVA wastes with "equilibrated" water have been progressing, but the low levels of activity make detection of leachates difficult. We are planning to label ion exchange resins with Cs-137 and Tc-99 and to expose them to leaching by various equilibrated waters under steady-state and cyclic flow.

Please call me if you have any questions.

Yours sincerely,

Geoffrey G. Eichholz
Regents' Professor

GGE/vw

cc: J. Detwiler (DOE-IOO)
R. L. Dodge (EG&G Idaho)
W. F. Brown (OCA)

Leach tests on TVA wastes and technetium-labeled material are progressing with no particular results of significance so far. This work continues.

Please call me if you have any questions.

Yours sincerely,

Geoffrey G. Eichholz
Regents' Professor

GGE:ctm

cc: J. Detwiler (DOE-IOO)
R. L. Dodge (EG&G-Idaho)
W. F. Brown (OCA)

Georgia Institute of Technology

A UNIT OF THE UNIVERSITY SYSTEM OF GEORGIA
SCHOOL OF NUCLEAR ENGINEERING AND HEALTH PHYSICS
ATLANTA, GEORGIA 30332

(404) 894-3720

March 9, 1984

Mr. Michael J. Barainca
Radioactive Waste Technology Branch
U.S. Department of Energy
Idaho Operations Office
550 Second Street
Idaho Falls, ID 83401

<u>Tenth Monthly Progress Letter</u>
Project No. 07-83ID12449; Our Project No. E-26-616

Dear Mr. Barainca:

Several modifications had to be made to the test bed to stabilize the trench walls and to minimize water infiltration along the bank. Further experience with the tensiometers has resulted in more consistent readings and a clearer understanding of the results of inclined insertion. The bed has been filled with about one foot of clean construction sand, which has been screened, sized and classified. This will serve for preliminary tests on bed drying and on procedure for determining moisture profiles. It is proposed to extend these tests to deeper columns once we are satisfied with the present set-up. At a later stage moisture profiles and water balances will be obtained for clay-containing soils.

Moisture tests on various sand and soil columns have been continued to correlate conductivity measurements and moisture content. It was found that pore size was relatively unimportant in determining residual moisture levels, but, as expected, the residual level increased for higher clay contents. However, it is not clear if that additional water content is merely absorbed internally in clay particles, in which case it may not contribute to waste migration, though it may affect leach rates. These points are expected to be studied in the coming months.

Georgia Institute of Technology
A UNIT OF THE UNIVERSITY SYSTEM OF GEORGIA
SCHOOL OF MECHANICAL ENGINEERING

May 9, 1984

Please reply to:

NUCLEAR ENGINEERING AND
HEALTH PHYSICS PROGRAM
CHERRY EMERSON BUILDING
GEORGIA INST. OF TECH.
ATLANTA, GEORGIA 30332 U.S.A.

Mr. Michael J. Barainca
Radioactive Waste Technology Branch
U.S. Department of Energy
Idaho Operations Office
550 Second Street
Idaho Falls, Idaho 83401

~~Twelfth~~ Eleventh Monthly Progress Letter
Project No. U/831D12449; Our Project No E-26-616

Dear Mr. Barainca:

Only slow progress was made in improving the outside test bed during the past month, partly owing to the unusual wet and stormy weather. A greatly improved drain pan has been constructed and is being installed at the moment. The tensiometers have been calibrated and electrodes have been made for correlations with conductivity measurements to establish moisture profiles.

The unsaturated-flow computer model, which is being developed in conjunction with another project, is also being adapted to model flow in the drained test bed and should prove useful in interpreting flow results.

New resin samples have been prepared that have been labeled with Cs-137 and Tc-99 and are undergoing leach tests in various equilibrated waters.

Yours Sincerely,

G.G. Eichholz
Regents' Professor

cc: J. Detwiler (DOE -IOO)
R.L. Dodge (EG&G Idaho)
O.H. Rodgers (OCA)

GGE/sm

Georgia Institute of Technology
A UNIT OF THE UNIVERSITY SYSTEM OF GEORGIA
SCHOOL OF NUCLEAR ENGINEERING AND HEALTH PHYSICS
ATLANTA, GEORGIA 30332
(404) 894-3720

October 10, 1983

Mr. Michael J. Barainca
Radioactive Waste Technology Branch
U.S. Dept. of Energy
Idaho Operations Office
550 Second St.
Idaho Falls, ID 83401

Fifth Monthly Progress Letter
Project No. 07-83ID12449; Our Project No. E-26-616

Dear Mr. Barainca:

Work on the project continued a little more slowly than anticipated during the past month, mainly because of the quarter break and the start of the new academic year. The test trench design is essentially complete, the gravel drain capacity has been estimated and a site location has been picked. We expect to excavate the trench within the next two weeks. A rough sketch of the trench is attached.

Work has continued on test columns to relate electrical conductivity and moisture content in sand columns. Further tests have also been done on Sequoyah Waste samples. The samples contain Cs-137, Co-60 and Cr-51, but at this stage it appears that the specific activity is too low for suitability as small leach test samples.

The literature search is essentially complete, with merely additions from current reports anticipated.

Yours sincerely,

Geoffrey G. Eichholz
Project Director

GGE/vw
Attachment

cc: J. Detwiler (DOE-IOO)
R. L. Dodge (EG&G Idaho)
W. F. Brown (OCA)

E-26-616

Georgia Institute of Technology

A UNIT OF THE UNIVERSITY SYSTEM OF GEORGIA

SCHOOL OF MECHANICAL ENGINEERING

June 11, 1984

Please reply to:

NUCLEAR ENGINEERING AND
HEALTH PHYSICS PROGRAM
CHERRY EMERSON BUILDING
GEORGIA INST. OF TECH.
ATLANTA, GEORGIA 30332 U.S.A.

Mr. Michael J. Barainca
Radioactive Waste Technology Branch
U.S. Department of Energy
Idaho Operations Office
550 Second Street
Idaho Falls, Idaho 83401

Twelfth Monthly Progress Letter
Project No. U/831D12449; Our Project No E-26-616

Dear Mr. Barainca:

After some unexpected delays, the test bed has been put together again with some improvements in base support, added front drainage and revetting of the side walls. A one-foot bed has been installed initially and its drainage profile is being monitored by means of tensiometers and conductivity probes. We are looking at alternative commercial materials to minimize silt migration from the waste bed into the gravel layer. We expect to obtain usable moisture profiles for increasing bed thicknesses and intend to correlate these results with laboratory tests on drainage rates and residual moisture for different soil types and hydraulic conductivities.

Tests are continuing on Tc-99 and Cs-137 labeled mixed-bed resin samples under steady flow conditions. As soon as steady conditions are established, we intend to simulate cyclic leach conditions for various wet/dry cycles. Please let me know if you have any questions.

Yours sincerely,

G. G. Eichholz
Regents' Professor

GGE/swm

cc: J. Detwiler (DOE - IOO)
R. L. Dodge (EG&G Idaho)
O. H. Rodgers (OCA)

Georgia Institute of Technology
A UNIT OF THE UNIVERSITY SYSTEM OF GEORGIA
SCHOOL OF MECHANICAL ENGINEERING

July 10, 1984

Please reply to:

NUCLEAR ENGINEERING AND
HEALTH PHYSICS PROGRAM
CHERRY EMERSON BUILDING
GEORGIA INST. OF TECH.
ATLANTA, GEORGIA 30332 U.S.A.

Mr. Michael J. Barainca
Radioactive Waste Technology Branch
U.S. Department of Energy
Idaho Operations Office
550 Second Street
Idaho Falls, Idaho 83401

Thirteenth Monthly Progress Letter
Project No. U/831D12449; Our Project No. E-26-616/E-25-645

Dear Mr. Barainca:

During the past month both the test bed observations and the baseline leaching test proceeded smoothly. The observations on the moisture profile have been supplemented by extensive laboratory column tests to correlate residual moisture levels with known soil properties. The measurements are also used to test the unsaturated flow model which is being developed as part of a related project. Ideally, it is hoped to derive from the measurements a draining coefficient as a function of moisture content above residual, which would help predict flow conditions in the test bed and enable us to use the flow model to determine residual water content as a function of time.

Additional resin samples have been prepared for several parallel flow tests under pulsed flow conditions. Several commercial trench liner materials have also been obtained and are being evaluated for use in the test bed.

Please let me know if you have any questions.

Yours sincerely,

G.G. Eichholz
Regents' Professor

GGE/sm

cc: J. Detwiler (DOE-IOO)
R.L. Dodge (EG&G Idaho)
O.H. Rodgers (OCA)

Georgia Institute of Technology
A UNIT OF THE UNIVERSITY SYSTEM OF GEORGIA
SCHOOL OF MECHANICAL ENGINEERING
August 10, 1984

Please reply to:

NUCLEAR ENGINEERING AND
HEALTH PHYSICS PROGRAM
CHERRY EMERSON BUILDING
GEORGIA INST. OF TECH.
ATLANTA, GEORGIA 30332 U.S.A.

Mr. Michael J. Barainca
Radioactive Waste Technology Branch
U.S. Department of Energy
Idaho Operations Office
550 Second Street
Idaho Falls, Idaho 83401

Fourteenth Monthly Progress Letter
Project No. U/831D12449; Our Project No. E-26-616/E-25-645

Dear Mr. Barainca:

During the past month further measurements have been done with "Rollo" sand in the test bed and moisture profiles have been obtained despite relatively rapid drainage rates. Some difficulties were encountered with the conductivity probes, but this was traced back to problems with multiple electrical grounds and has been overcome. We are planning to replace the sand bed with a loamy soil next week and expect to get reproducible moisture profiles fairly rapidly.

Further laboratory tests have been done to measure moisture retention parameters as functions of pore size and adsorption characteristics and additional work has been done on the calculational model for unsaturated flow.

The leach tests have been converted to once-through tests with equilibrated waters, since it became evident that the water characteristics were changing too fast in the recirculation set-up used before, because of the presence of ion exchange resins to recover the desorbed tracer activities.

An abstract has been submitted for a paper to be presented at the LLW Participants Information Meeting next month and the paper itself is in process of being prepared.

Please let me know if you have any questions.

Yours sincerely,

G.G. Eichholz
Regents Professor

GGE/swm

cc: J. Detwiler (DOE-IOO)
R.L. Dodge (EG&G Idaho)
O.H. Rodgers (OCA)

E-26-616

Georgia Institute of Technology

A UNIT OF THE UNIVERSITY SYSTEM OF GEORGIA
SCHOOL OF MECHANICAL ENGINEERING

Please reply to:

NUCLEAR ENGINEERING AND
HEALTH PHYSICS PROGRAM
CHERRY EMERSON BUILDING
GEORGIA INST. OF TECH.
ATLANTA, GEORGIA 30332 U.S.A.

September 7, 1984

Mr. Michael J. Barainca
Radioactive Waste Technology Branch
U.S. Department of Energy
Idaho Operations Office
550 Second Street
Idaho Falls, Idaho 83401

~~Fourteenth~~ Fifteenth Monthly Progress Letter
Project No. U/831D12449; Our Project No. E-26-616/E-25-645

Dear Mr. Barainca:

During the past month, further test bed data have been obtained on drainage coeffecents and moisture profiles and two types of sand (Rollo and GT). Conductivity probes have been calibrated for the two SRP sand samples and tests with one of these are expected to start shortly. Recalibrations have been necessary because of differences in the water supplies in the lab and in the field. Conduction conditions were found to be relatively independent of the degree of compaction. The nature of the supporting material was found to be important and this has a bearing on the design of a drainable waste trench.

Much of this material has been organized for a paper to be presented at the LLWMP Partipants Information meeting in Denver next week and the preparation of this paper required a major effort.

Work is proceeding on leach tests on simulated waste, but the procedure has been changed to a once-through apprach to avoid steady modification in water conditions; however, this calls for a larger supply of equilibrated water.

I look forward to discussing progress on this project, and any possible extension, with you and Mr. Dodge at the meeting next week.

Yours sincerely,

G. G. Eichholz
Regents' Professor

GGE/ch
Cc: J. Detwiler (DOE-IOO)
R. L. Dodge (EG&G Idaho)
O. H. Rodgers (OCA)

Georgia Institute of Technology
A UNIT OF THE UNIVERSITY SYSTEM OF GEORGIA
SCHOOL OF MECHANICAL ENGINEERING

October 9, 1984

Please reply to:

NUCLEAR ENGINEERING AND
HEALTH PHYSICS PROGRAM
CHERRY EMERSON BUILDING
GEORGIA INST. OF TECH.
ATLANTA, GEORGIA 30332 U.S.A.

Mr. Michael J. Barainca
Radioactive Waste Technology Branch
U.S. Department of Energy
Idaho Operations Office
550 Second Street
Idaho Falls, Idaho 83401

~~Fifteenth~~ Sixteenth Monthly Progress Letter
Project No. U /831D12449; Our Project No. E-26-616/~~E-25-645~~

Dear Mr. Barainca:

The past month saw the presentation of a summary paper on the project at the DOE/LLWMP Participants Information Meeting in Denver, which seemed to be well received.

Since then we have formulated the design drain structure in a little more detail and, in particular, have obtained some "89 Stone" for study as an appropriate gravel base.

The test bed is being partly filled with a local soil which has intermediate sand/clay composition between the Rollo sand and the SRP soil. Its properties are being characterized at the moment.

We have resumed leach testing with simulated resin waste and expect to have some results on leach rate dependence on the wetting cycle shortly.

In laboratory tests we are performing some studies to obtain drainage coefficients and suction terms for insertion into the computer models. During the coming weeks we are planning some radioactive tracer tests in laboratory columns to compare retardation rates due to absorption on soil surfaces with the other time - dependent rate constants.

We have submitted a draft research proposal to Mr. Dodge for his comments, which covers a possible extension of this work to gain a better understanding of the migration rate constants and leach rate variations under unsaturated flow conditions. We hope to be able to submit a formal proposal to you in time to facilitate a smooth transition after the present contract expires.

Please let me know if you have any questions.

Yours sincerely,

G.G. Eichholz
Regents' Professor

CGE/ch
cc: J. Detwiler (DOE-100)
R.L. Dodge (EG&G Idaho)
O.H. Rodgers (OCA)

Georgia Institute of Technology
A UNIT OF THE UNIVERSITY SYSTEM OF GEORGIA
SCHOOL OF MECHANICAL ENGINEERING
November 8, 1984

Please reply to:

NUCLEAR ENGINEERING AND
HEALTH PHYSICS PROGRAM
CHERRY EMERSON BUILDING
GEORGIA INST. OF TECH.
ATLANTA, GEORGIA 30332 U.S.A.

Mr. Michael J. Barainca
Radioactive Waste Technology Branch
U.S. Department of Energy
Idaho Operations Office
550 Second Street
Idaho Falls, Idaho 83401

~~Fifteenth~~ Seventeenth Monthly Progress Letter
Project No. U /831D12449; Our Project No. E-26-616/E-25-645

Dear Mr. Barainca:

During the past month tests have been conducted on the test bed with an "intermediate" soil material which was prepared by careful blending of Georgia Tech soil and a high-clay soil to provide some intermediate drainage and suction coefficients between sand runs and "SRP soil" runs. This should be of help in providing input data to the one-dimensional computer model.

That model has been run and tested for saturated "boundary conditions" and is being run at present for increasingly lower moisture contents. In conjunction with those runs we are also starting some radioactive tracer tests on laboratory columns to obtain independent retardation values for the particular soils used by us.

The leach tests have been resumed under, hopefully, more reproducible conditions and we expect to obtain comparison runs under pulse flow conditions.

During the next few weeks we expect to correlate our data and to draft our final report on this project. Please let us know if you wish to see a draft version or whether we should simply submit our final report.

We hope to receive favorable comments from the LLWMP group regarding our tentative proposal for a more generic project to continue our evaluation of unsaturated flow conditions, in their relation to source term modifications and their effect on waste migration. If this proposal is acceptable we plan to submit a formal proposal to you shortly.

Please let me know if you have any questions

Yours sincerely,

G.G. Eichholz
Regents Professor

GGE/swm
cc: J. Detwiler (DOE-100)
R.L. Dodge (EG&G Idaho)
O.H. Rodgers (OCA)

Final E-25-606

EVALUATION AND DESIGN OF DRAINED LOW-LEVEL RADIOACTIVE DISPOSAL SITES

FINAL REPORT

PROJECT E25-606, CONTRACT NO. DE-AS07-83ID12449

edited by

Geoffrey G. Eichholz
Project Director

submitted to

U.S. DEPARTMENT OF ENERGY
Idaho Operations Office
Idaho Falls, ID 83401

Program in Nuclear Engineering & Health Physics
Georgia Institute of Technology
Atlanta, GA 30332

December, 1984

CONTENTS

LIST OF FIGURES

Figure 33 Diagram of Migration Model

SUMMARY

Low-level waste disposal in shallow trenches has been the subject of much critical assessment in recent years. Historically most trenches have been located in fairly permeable settings and any liquid waste stored has migrated at rates limited mainly by hydraulic effects and the ion exchange capacity of underlying soil minerals. Attempts to minimize such seepage by choosing sites in very impermeable settings lead to overflow and surface runoff, whenever the trench cap is breached by subsidence or erosion.

The work undertaken in the project described in this report was directed to an optimum compromise situation where less reliance is placed on cap permanence, any ground seepage is directed and controlled, and the amount of waste leaching that would occur is minimized by keeping the soil surrounding the waste at all times at only residual moisture levels.

Measurements have been conducted to determine these residual levels for some representative soils, to estimate the impact on waste migration of high unsaturated flow conditions and to generate a conceptual design of a disposal facility which would provide adequate drainage to keep the waste from being exposed to continuous leaching by standing water. An attempt has also been made to quantify the reduced source terms under such periodic, unsaturated flow conditions, but those tests have not been conclusive to date.

Since most disposal sites even in humid regions of the United States are exposed only to intermittent rainfall and as most trench designs incorporate some gravel base for drainage, the results of this project have broader applications in assessing actual migration conditions in shallow trench disposal sites.

Project Personnel
(all parttime)

Geoffrey G. Eichholz, Ph.D.	Project Director
T. Fisher Craft, Ph.D.	Senior Research Scientist
M. Frank Petelka, M.S.H.P.	Graduate Research Assistant
Jooho Whang, M.S.H.P.	Graduate Research Assistant
Fernando N. deSousa, M.S.H.P.	Graduate Research Assistant
Marino C. Kaminski, B.S.	Graduate Research Assistant
Bonny A. Wright, B.S.H.P.	Graduate Research Assistant
Denise D. Hardy, B.S.	Graduate Research Assistant
Martha R. Poston, B.S.H.P.	Graduate Research Assistant
Hobert W. Jones, B.S.	Graduate Research Assistant
Bruce W. Patton, B.S.	Graduate Research Assistant

Some of the work was shared with a parallel project conducted for the Savannah River Laboratory.

INTRODUCTION

Shallow land burial of low-level radioactive wastes has been practiced since the early days of the U.S. atomic energy program. Unfortunately, early programs were only required to meet "maximum permissible concentration" standards for any nuclear facility effluents and very little control was effected on site inventory and waste form. As a consequence, many of those sites contained liquid wastes which seeped into the ground, where they were retained primarily by ion exchange and adsorption processes on mineral surfaces. The appearance of low levels of radioactive materials, especially tritium, in groundwaters offsite drew public attention to disposal conditions that were insufficiently controlled by more recent standards and as a consequence waste disposal of low-level waste was looked on by the public with disfavor as a potential source of hazardous contamination of groundwater. To meet these objections the U.S. Nuclear Regulatory Commission has issued guidelines, under Title 10 Code of Federal Regulations Part 61, that prescribe waste form characteristics and site suitability criteria, but no quantitative performance objectives. The U.S. Environmental Protection Agency, on the other hand, is in the process of specifying effluent concentration levels under Hazardous Waste Regulations (40CFR 122,265) or the Resource Conservation and Recovery Act (RCRA).

In either case, performance assessment depends on a good understanding of the mechanisms that govern mobilization and migration of the waste materials through soil or fractured rock into any accessible aquifer, since groundwater transport is the only feasible pathway, other than deliberate or accidental intrusion, by which the waste materials can return to the accessible environment. Most of the calculational models described in the literature assume, that sooner or later water infiltrates the burial trench, saturates the soil, leaches some of the waste at a rate controlled mainly by solubility considerations, and that the dissolved waste travels with the water, subject to retardation by surface adsorption on surrounding minerals, until an aquifer is reached, through which in due course it may reach the surface, in springs or wells, to enter the food chain.

Control of this process, in 10CFR61 and related documents, is envisaged primarily by four precautions: 1.use of a solid waste form, that, hopefully, is not excessively subject to dissolution; 2.waste deposition well above the water table; 3.use of an impermeable soil formation to minimize water flow towards the aquifer; and 4.installation of a stable impermeable trench cap to inhibit or retard water infiltration into the trench.

These approaches are illustrated in Figures 1 and 2 (Refs. 1 & 2) which illustrate diagrammatically the main elements of such a trench. In Figure 1 additional lining is introduced to contain water in the trench.

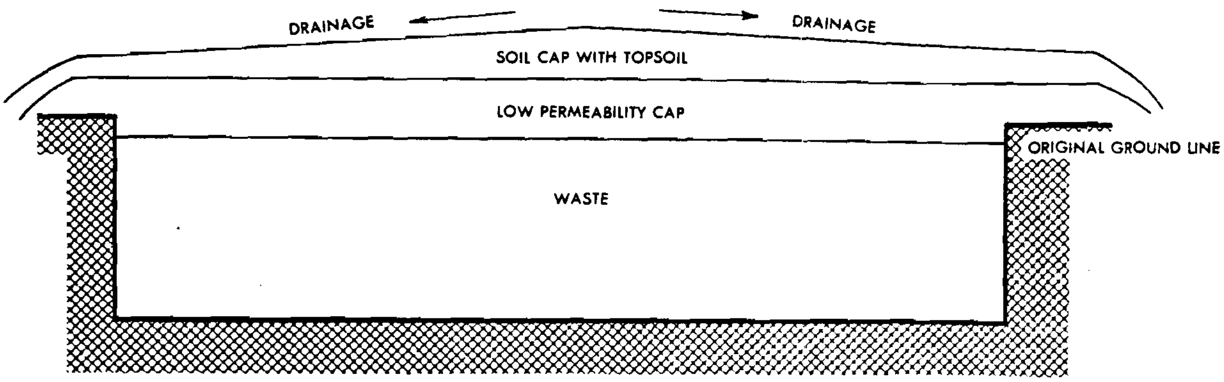


Figure 1a Closed trench with soil cap, showing cap drainage

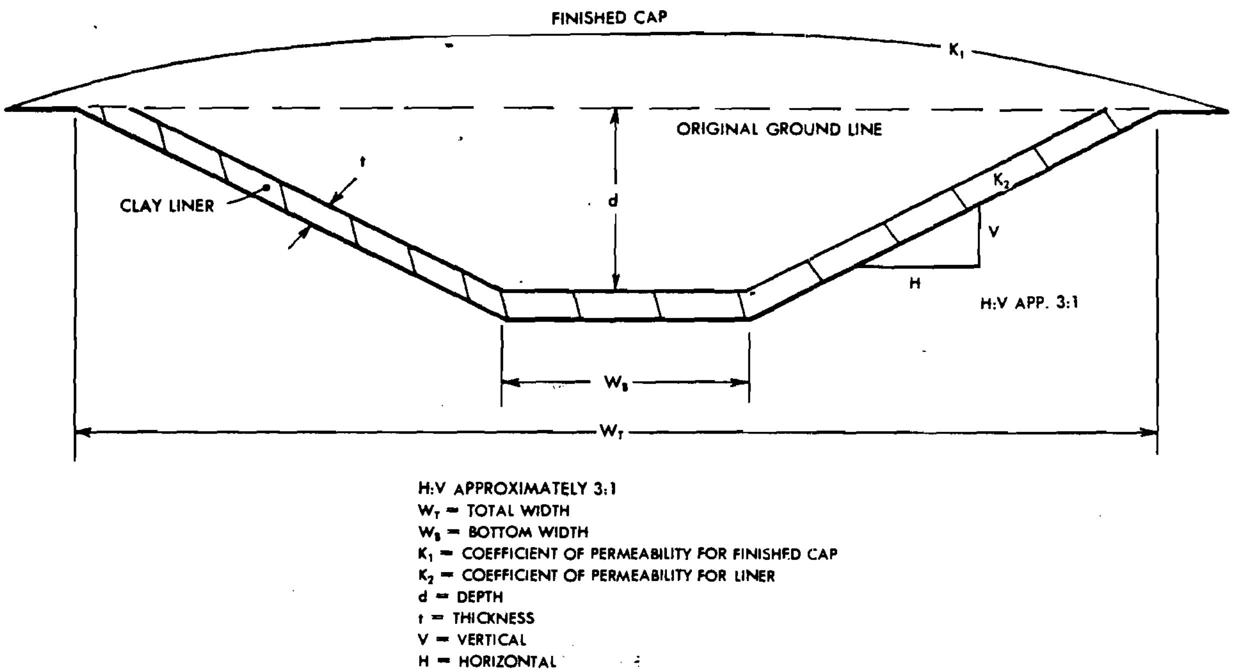


Figure 1b Clay bottom liner (Ref. 1)

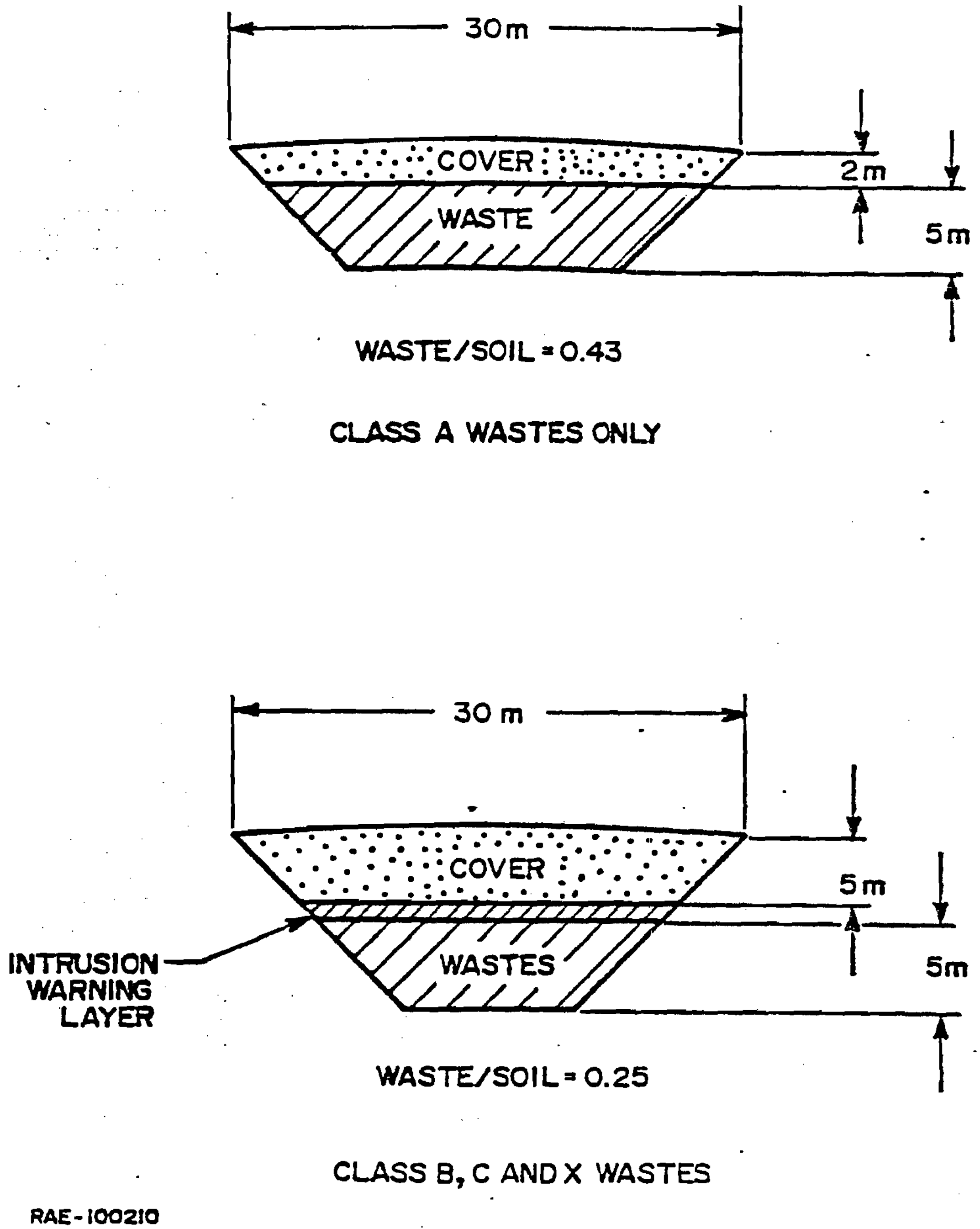


Figure 2 Trench designs for shallow aquifer and arid site (Ref. 2)

Figure 2 also shows a possible warning layer "to deter intruders". Short of actually concreting the walls or the trench bottom, some seepage ultimately will occur with a plume following the hydraulic gradient in the water table (Fig 3, from Ref.3). Figure 4(Ref.3) illustrates the actual construction of some shallow trenches.

Several problems can arise in this approach. First of all, the trench cap will tend to collapse or erode in time, due to consolidation or compaction of the waste materials and the interstices between them, settling of backfill soil, and the effect of surface water. This means that sooner or later water will enter the trench unless very elaborate cap structures are devised. Figures 5 and 6 give examples of such cap designs, which add enormously to the cost of disposal and are almost equivalent to the surface bunker retrievable storage concept.

The second problem arises from the fact, that with a highly impermeable base formation any infiltrated water in the trench has nowhere to go and sooner or later will fill the trench and overflow. This "bath tub effect" has been observed at some sites and results in surface flow of trench water, instead of downward seepage towards the water table, and an early return to the accessible environment of potentially contaminated water. In addition, the waste would find itself engulfed by standing water so that any leaching effects would be greatly increased. Abatement of the bath tub effect by reliance on even more elaborate cap structures is questionable and expensive, particularly since there is no guarantee that lateral inflow into the trench would not occur. McCray et al. (Ref.5) have reported observations on such interflow.

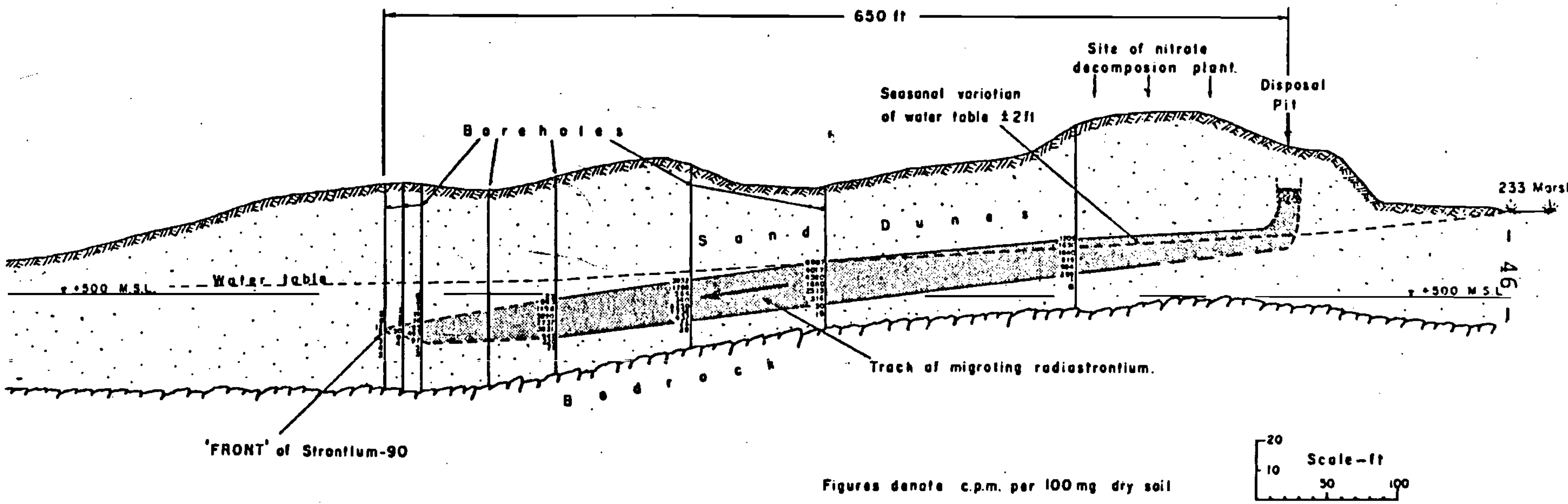
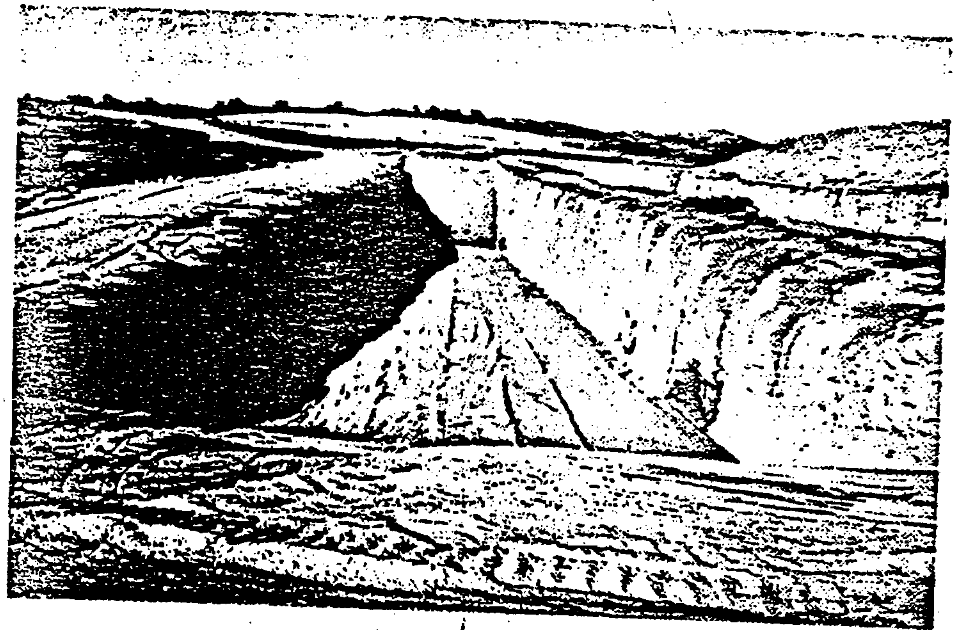
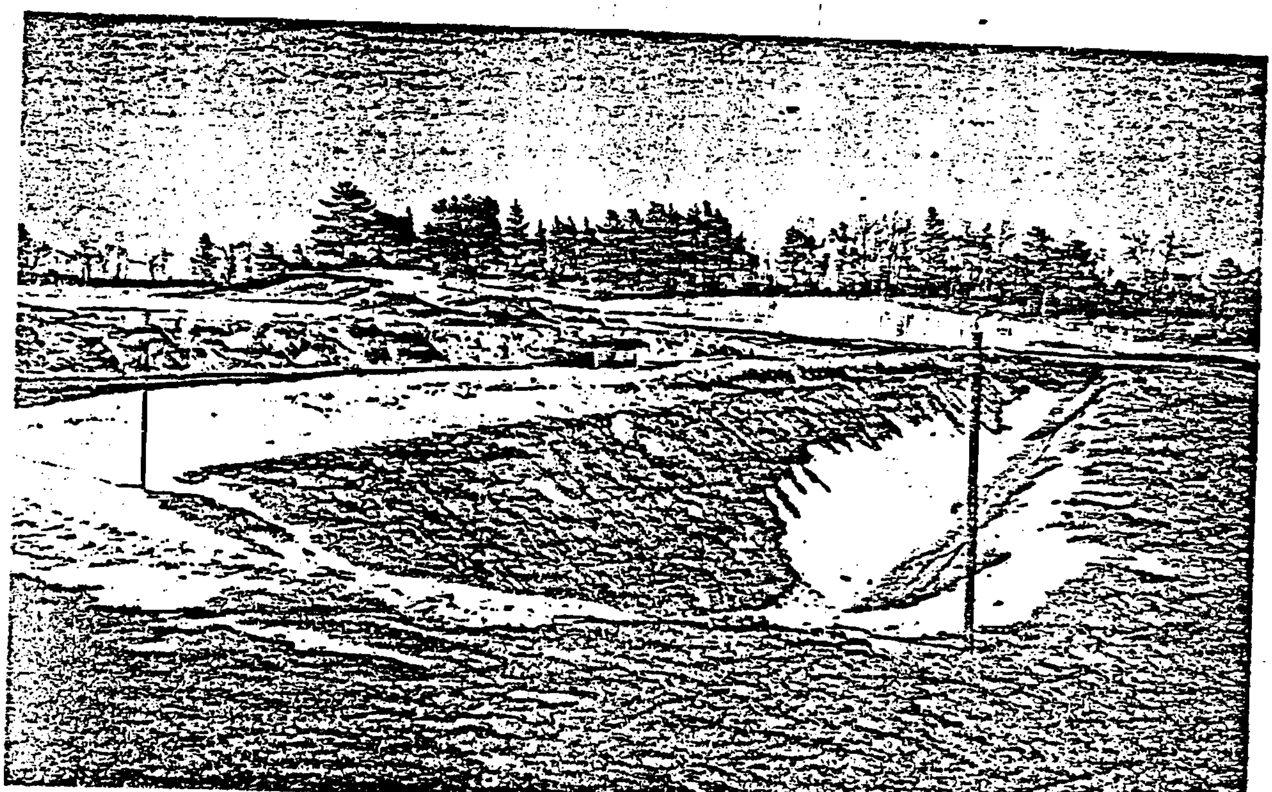


Figure 3 Section along track of migrating radionuclides (Ref 3)



Waste Burial Pit at the Los Alamos Scientific Laboratory (New Mexico, USA) Dug into Tuff (180 x 15 x 8 m Deep). Note Steep Slope and Relatively Clean Cut Walls [11]



A Trench Dug into Sand in Area "C" at CRNL Showing Shallow Sloped Walls

Figure 4 Views of two burial sites (from Ref. 3)

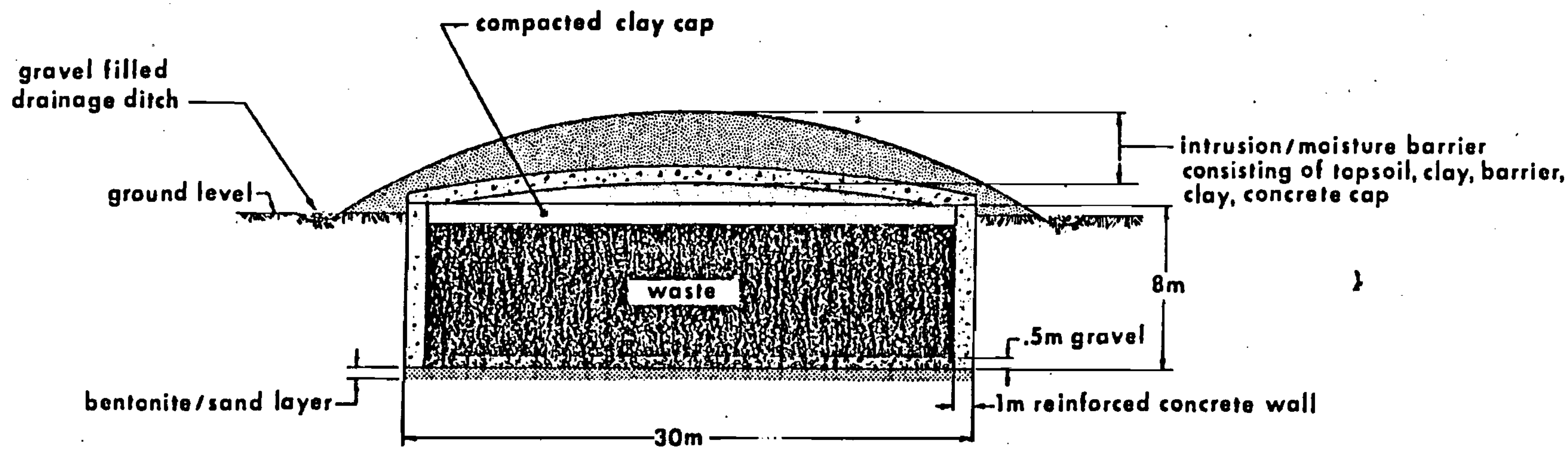


Figure 5 Cross section through concrete vault facility (Ref. 3)

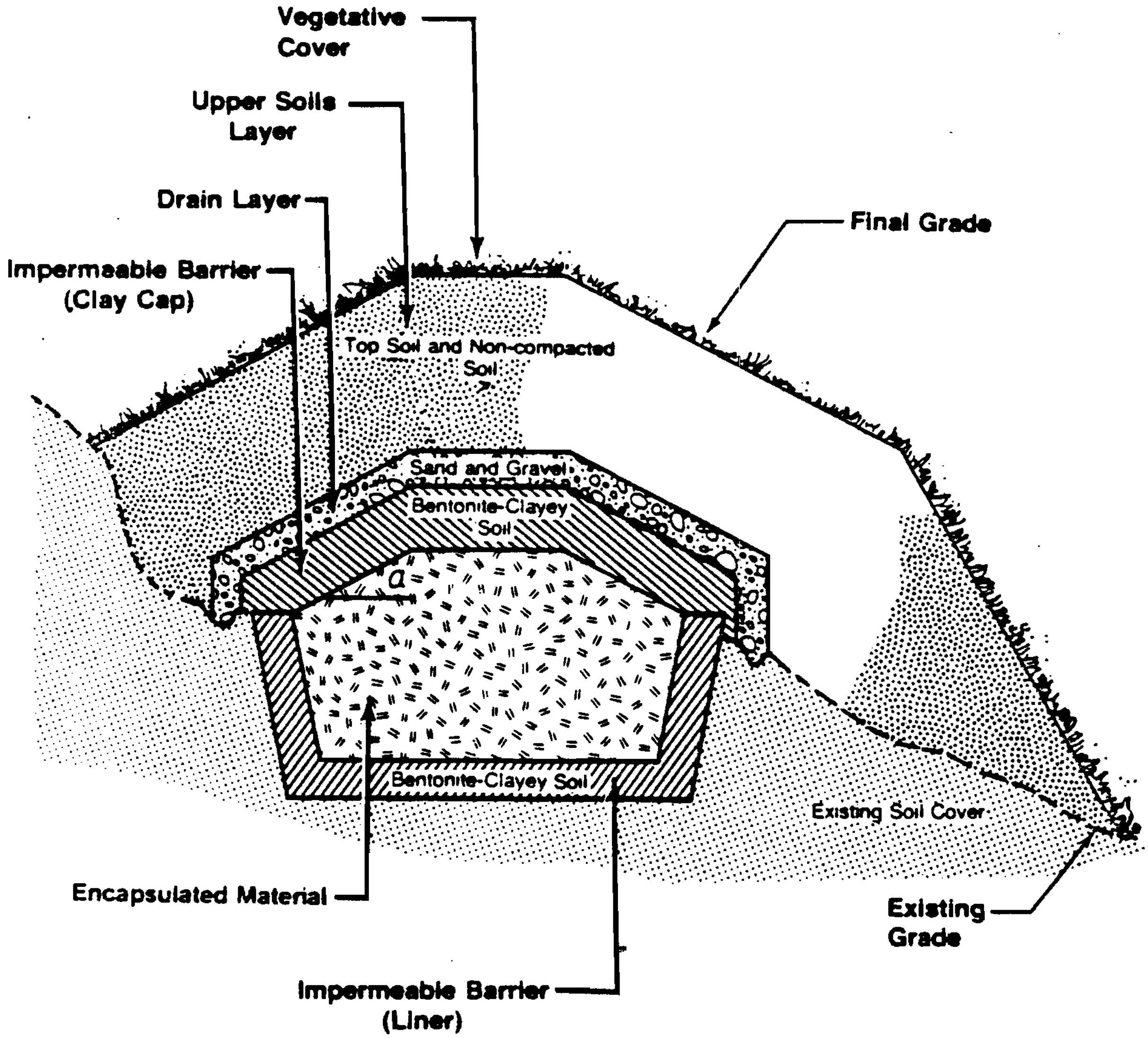


Figure 6 Profile of encapsulation and cover - Canonsburg site (Ref. 4)

a – **Slope Angle**

An alternative way of dealing with the threat of a bath tub effect is by the installation of drains, combined in some cases by deliberate pumping from the trenches. This approach is illustrated in Figure 7 (Ref. 2), where the pump well is also used for monitoring purposes, and has been proposed for the Central Disposal Facility at Oak Ridge for hazardous wastes (Ref. 6). For the Canonsburg site, Metry et al. (Ref. 4) also propose a near-surface drain to minimize infiltration, see Figure 8.

In the work described in this report this approach has been taken a stage further by allowing the drained-off water to seep into the ground along a predetermined seepage path. This eliminates the need for active pumping which would normally be impractical after closure of the site. By also selecting conditions promoting easy drainage, one also minimizes the amount of moisture in contact with the waste, so that leaching effects may be greatly reduced, resulting in a much smaller source term for any hazard prediction. This project has been concerned with studying the effects of avoiding high water content in the waste area on leach effects and model calculations and with a consideration of conceptual designs for this approach.

A preliminary account of this work was presented at the DOE Participants Meeting in Denver in September, 1984 (Ref. 7).

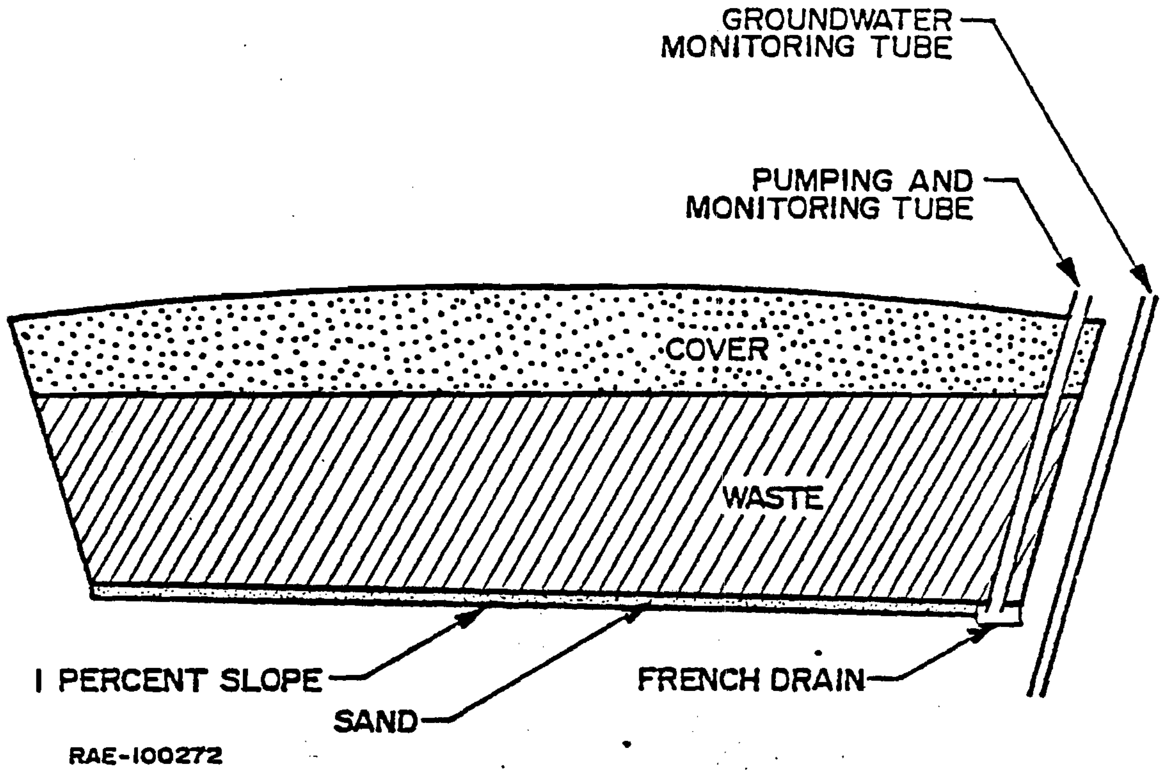


FIGURE 7-a. CROSS SECTION OF TYPICAL TRENCH

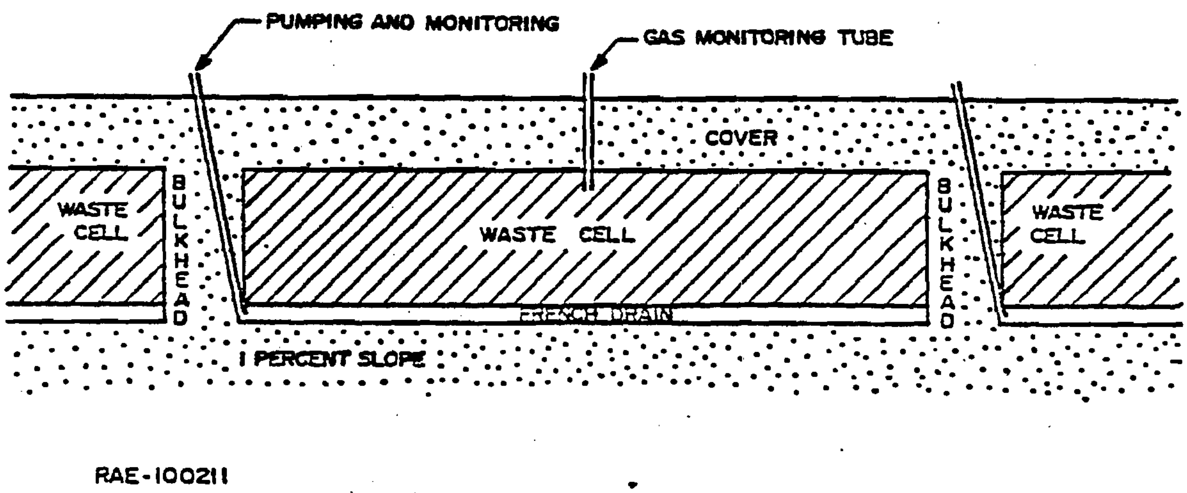


FIGURE 7-b. SECTION OF TYPICAL TRENCH ALONG ITS LONG AXIS

Figure 7 Sections of typical drained trench (Ref. 2)

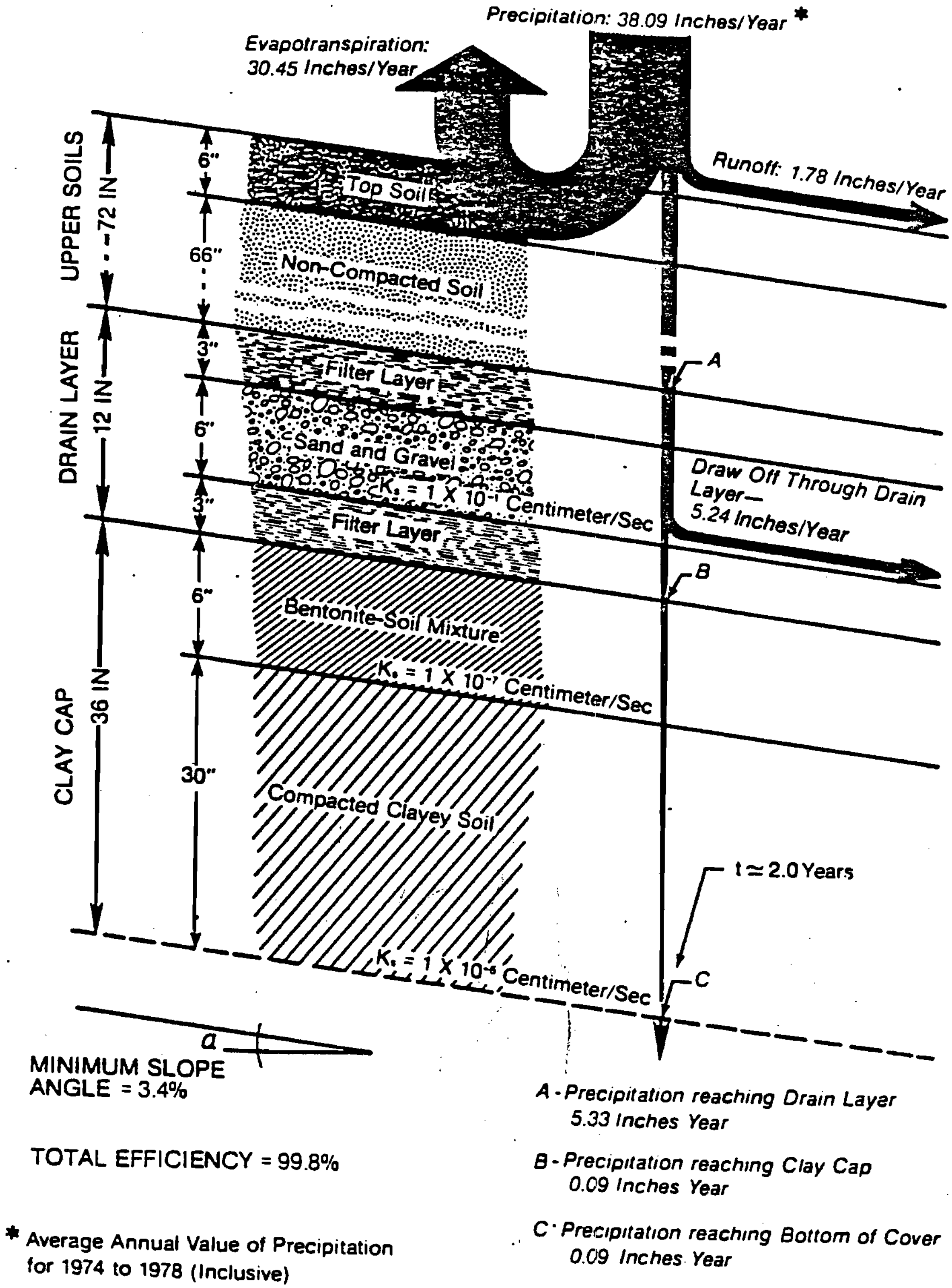


Figure 8 Water budget for cover system -- Canonsburg site (Ref. 4)

TRENCH HYDROLOGY

The hydrology of a burial trench is shown diagrammatically in Figure 9. A very high proportion of precipitated water is returned to the atmosphere by evaporation and evapotranspiration and only 20-25% or less will actually infiltrate the trench itself. Once there, water movement is subject to a balance of gravitational and capillary forces, though for fairly permeable backfill surrounding waste packages it is reasonable to assume a slow, but steady net downward flow. As this flow passes the buried wastes it is usually assumed that some leaching will occur, i.e. decontamination of buried waste material by the passing flow of water and dissolution of some radioactive materials, that may then remain in solution or adsorb on some fine suspended particulates that may be present. Self-retention within the backfill soil presumably occurs, but is rarely included in any assessment model.

Although 10CFR61 assumes location of the trench in an impermeable medium, any impact assessment ordinarily takes the finite permeability of the surrounding soil for granted and accepts it as the normal pathway for the dissolved waste ions or complexes (9,10). Innumerable measurements have been reported on the resultant flow through such soil and on retardation effects on the migration of any dissolved ions due to sorption-desorption effects on any mineral surfaces in contact with the water flow (11-15). These processes are generally considered part of the engineered barriers of the system, but invariably are assumed to be subject to saturated flow.

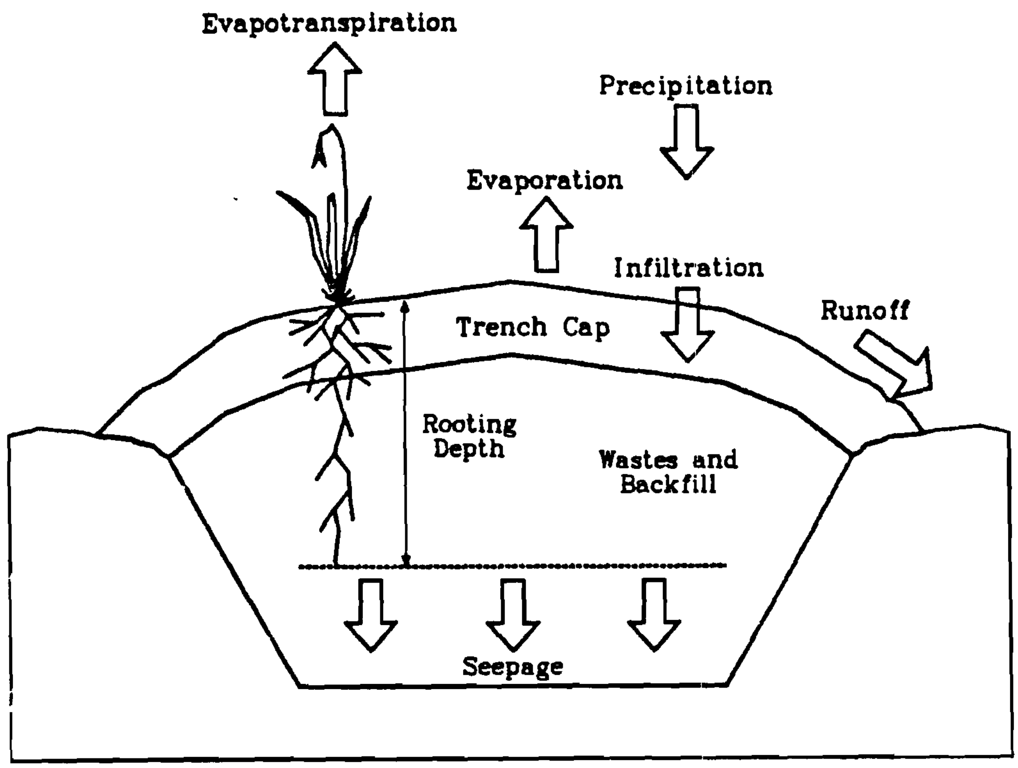


Figure 9 Hydrology of shallow land burial trench(from Ref. 7)

Actually, most soil systems will not be saturated unless the soil is unusually retentive or the water is allowed to back up, as in the bathtub situation (16). For arid sites in the Western U.S., soil saturation would be rare; this has been studied by the Los Alamos group (17-19). Figures 10 and 11 show variations in moisture profiles at Maxey Flats observed near the surface (0.9m) and at depth (2.4m). Strong seasonal variations are evident near the surface; a smooth curve exists at depth. In both cases moisture levels were well below saturation most of the time, though in the trench cap significant water retention occurred because of suction effects from its lower surface. Observations by Davis et al. (Fig. 12) also show that variations in the level of the water table following rainfall depend on rapid infiltration flow and only slow drainage rates (21). Thus, even in the "humid zone" of the Eastern United States unsaturated moisture conditions may prevail for much of the time, between heavy showers, as occur in the South, or during periods when the surface is frozen or snow-covered in the North. If the backfill and surrounding soils are fairly permeable, this implies that the waste may find itself in moderately dry surroundings much of the time and the time-averaged leach rate may be substantially different from that assumed for "conservative", saturated conditions. The present study was directed to investigate the benefits of reducing the ambient moisture levels around the waste as much as possible by accepting a periodic mode of infiltration and removing the major cause of water back up.

Migration of dissolved wastes under unsaturated conditions is a fairly complex process. In a clay-rich soil not all of the water present

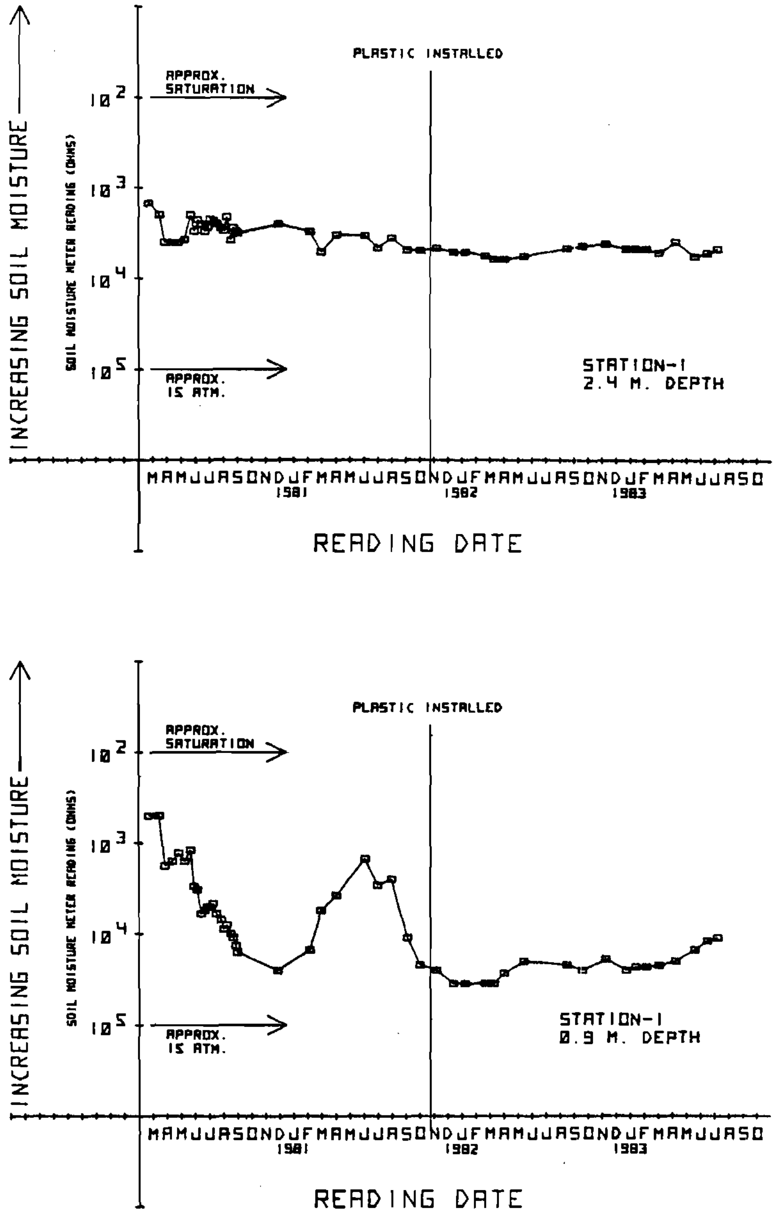
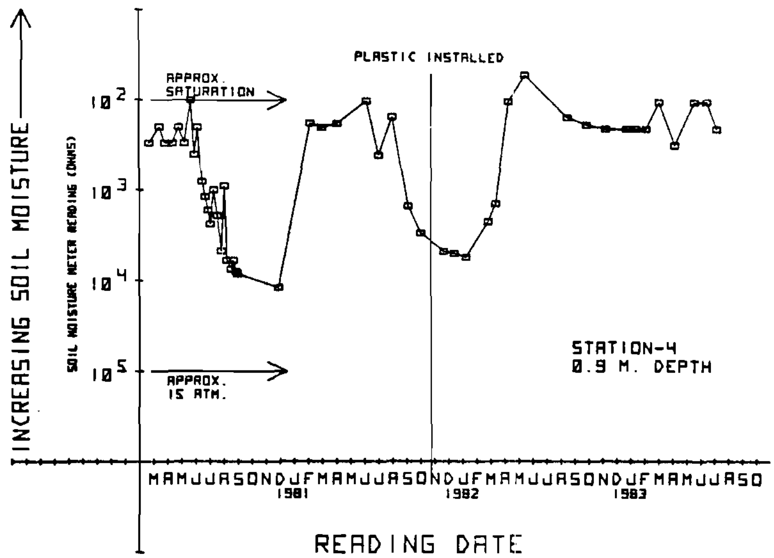


Figure 10 Soil moisture plots at Maxey Flats at two depths (Ref. 8)



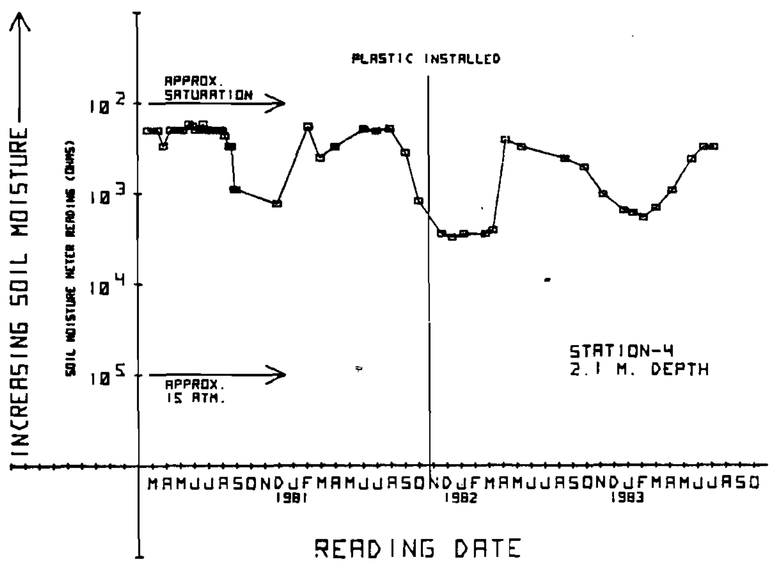


Figure 11 Soil moisture plots at two depths in a trench cap at Maxey Flats (Ref. 8)

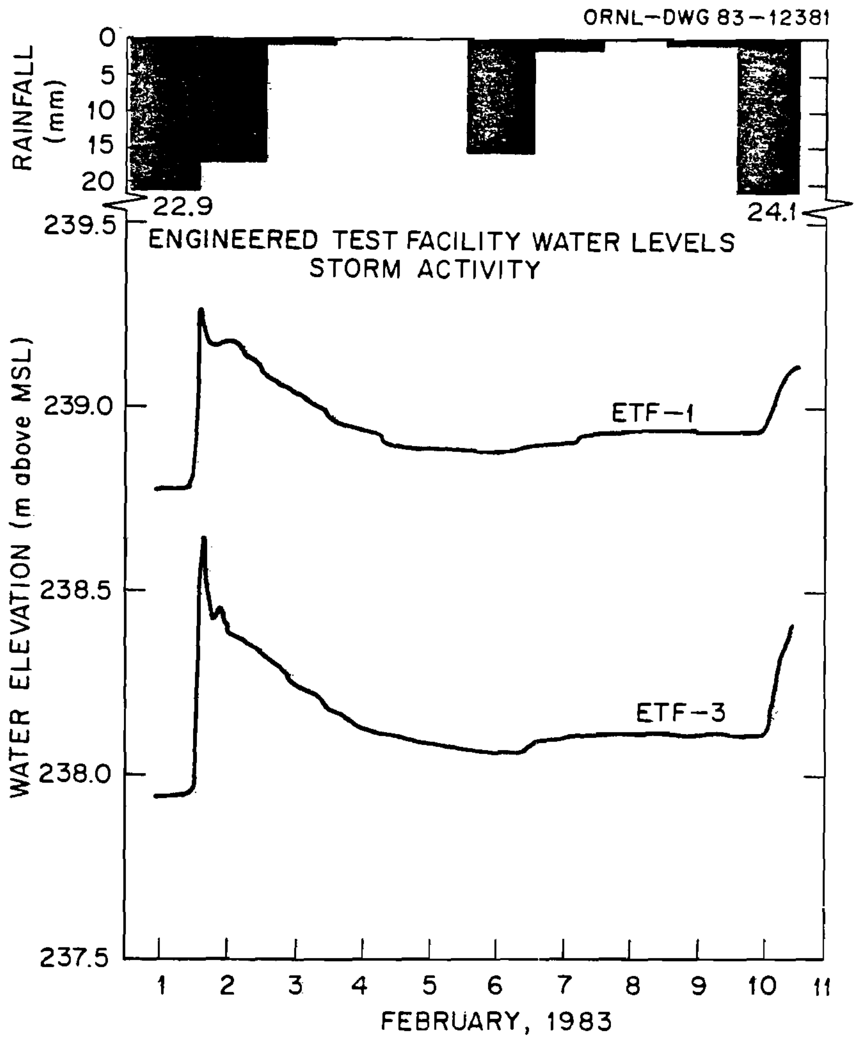


Figure 12 Groundwater response to rainfall for one week in February 1983 (Ref. 6)

in the soil is mobile, but may be bound in the clay structure. The mobile water may move slowly and would not fill all of the pores (22). As a result the volumetric flow rate for a given percent saturation value would not be proportional to the water content. As moisture content decreases the capillary force begins to predominate. This has two consequences:

1. Except in highly permeable, coarse materials, like coarse sand, the moisture level will reach a finite minimum residual moisture concentration, which depends on the hydraulic conductivity of the soil and, typically, its clay content, and which will be retained indefinitely at depths below those affected by evapotranspiration.
2. Above any major structural interface, a moist column will be retained by suction forces that may have a higher moisture content than the drained volume above. This leads to an effect of water flow around cavities, such as waste materials, reducing effectively the amount of water available for leaching. It also imposes a need to allow a soil layer above any built-in drain before emplacing wastes.

All of these effects have been studied in this project to the extent that they affect disposal trench design. The work undertaken in this project consisted of four main tasks:

a) Construction of a test bed to study the response of a soil column to steady or periodic infiltration under unsaturated flow conditions;
b) Development of a simple computer model to permit generalization of the data obtained;

c) Study of waste leaching conditions when exposed to unsaturated flow; and

d) Conceptual design of a shallow waste burial facility to minimize immersion of the waste material by the provision of drains and directing the off flow.

Various subsidiary tasks, such as characterization of soils, calibration of moisture probes, and code development benefited from parallel work going on under the sponsorship of the Savannah River Laboratory, EI Du Pont de Nemours & Co.

TEST BED CONSTRUCTION

One of the prime objectives of this investigation was the measurement and demonstration of flow and drainage conditions of representative soil columns under unsaturated conditions. Tests were also conducted on laboratory scale columns, but from the start it was considered essential to conduct field scale tests to minimize wall effects and drain interface effects.

The test bed was intended to be readily drained and to be accessible from one side to measure moisture profiles during the course of a run. It had to be easy to dismantle, capable of being layered if necessary, and subject to various methods of introducing water flow.

A site was chosen on a natural slope behind the Frank Neely Nuclear Research Center and the Electronics Research Building on the Georgia Tech Campus. Figure 13 is a sketch cross section of the trench. The bed itself consisted of a wooden box, 6ft high, 2 ft. x 2ft. in cross section which was installed in the trench cut whose walls had been lined with plastic sheet and braced. Figure 14 shows the major dimensions in plan. Figure 15 presents two stages in the construction of the trench and the installation of the test box. Some major problems were encountered in the construction and installation of the drain pan, which underwent several modifications. Similarly, experience led to various improvements in revetment of the trench walls and the sloping of the drainage bed at the bottom of the trench. The assistance of the Georgia Tech Physical Plant Department in cutting the trench and supplying gravel and other materials is gratefully acknowledged.

The front panel is removable for loading and unloading. Figure 16a shows a series of tensiometers that were installed to measure moisture profiles. The tensiometers were Soiltest Inc., Model 120; great care had to be taken in their installation to remove any residual air bubbles. It was found that the tensiometers were insufficiently responsive at low moisture concentrations and, for that reason, most later tests relied on electrical conductivity probes. Figure 16b shows the contact panel and meter for these probes on top of the test bed.

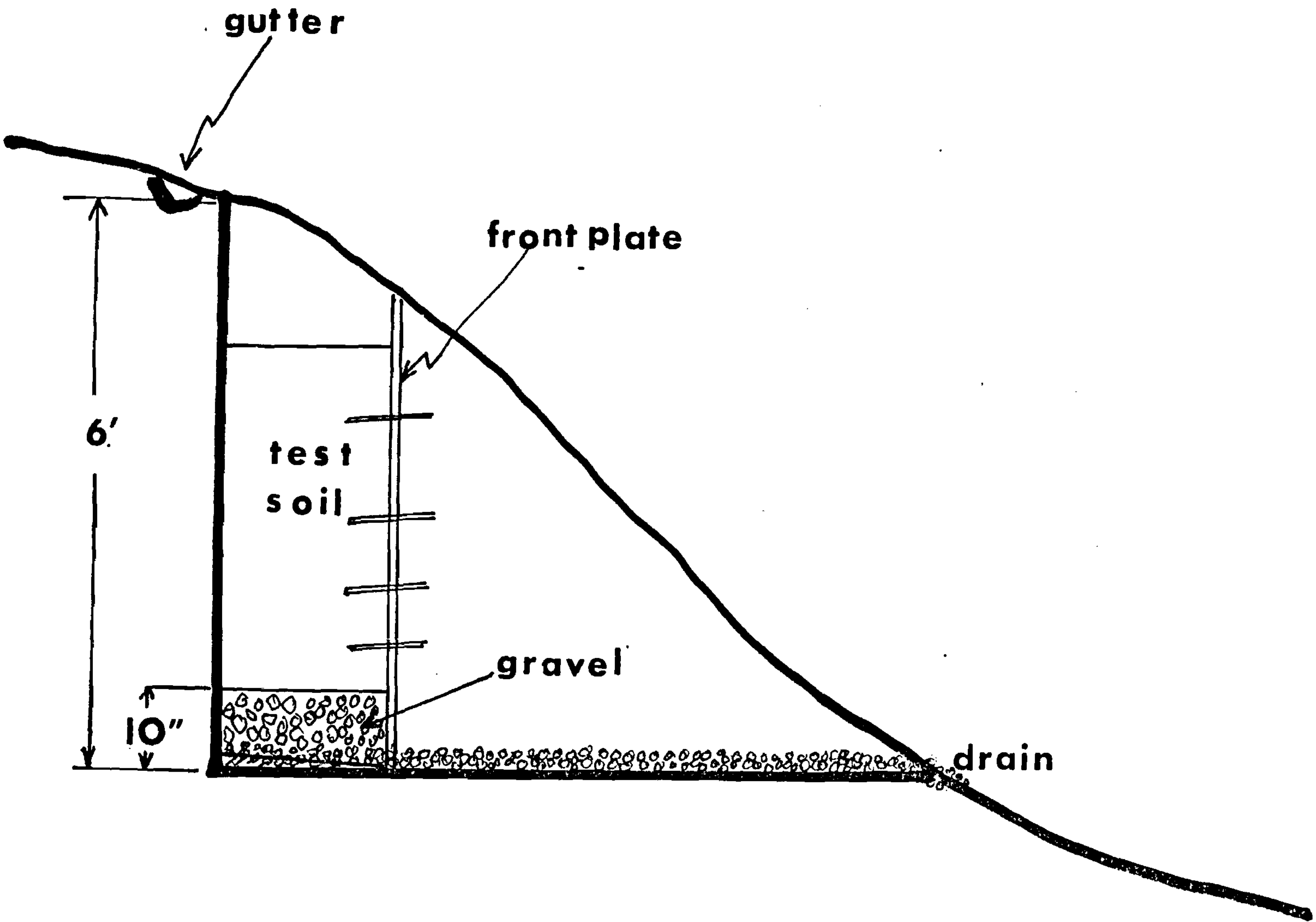


Figure 13 Cross section of Test bed trench

uphill

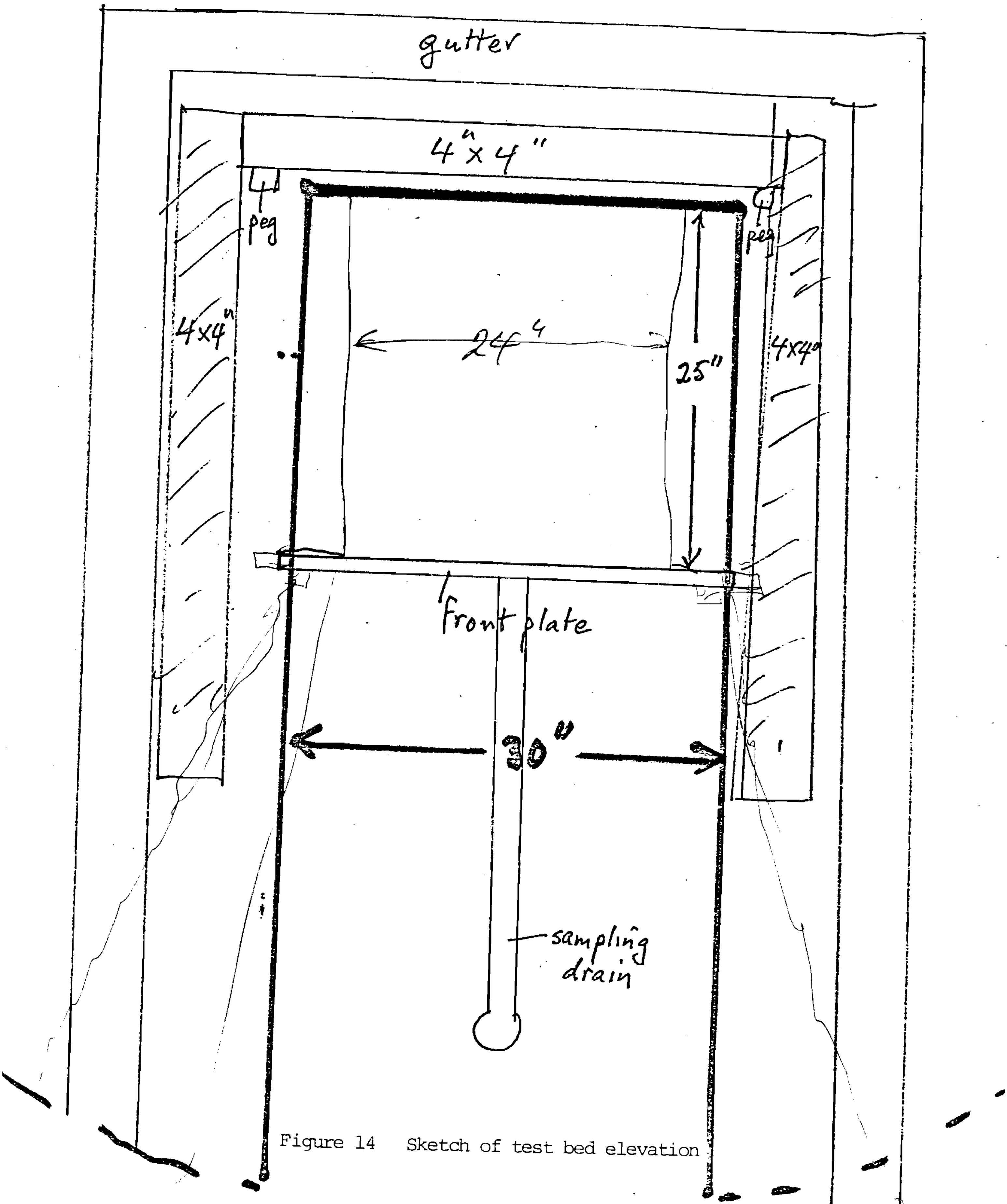


Figure 14 Sketch of test bed elevation

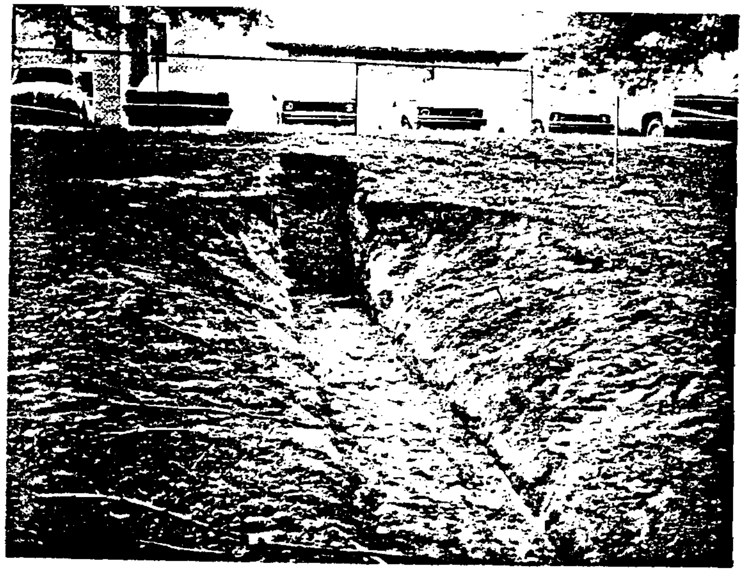


Figure 15 Views of test bed during construction

Figure 16 Views of instrumentation on test bed

MATERIALS

Test work was done with two types of sand, referred to as Rollo Sand and GT Sand, two types of fairly clayey soils, SRP No. 1 and No. 2, and a synthetic mixture, FP soil. Table 1 lists the basic properties and composition of these soils.

TABLE 1 - SOIL PROPERTIES

SOIL TYPE	BULK DENSITY (g/cm^3)	POROSITY	SAND FRACTION (%)	SILT FRACTION (%)	CLAY FRACTION (%)	SATURATED HYDRAULIC CONDUCTIVITY (cm/day)
Rollo Sand	1.4.0	0.472	98.9	1.1	0.0	—
G.T. Sand	1.38	0.479	97.4	2.6	0.0	2000
SRP #1	1.24	0.32	62.0	9.0	29.0	30
SRP #2	1.20	0.547	56.0	4.0	40.0	60
FP Soil	1.42	0.466	73.4	15.5	11.4	-

Particle size analyses were conducted and the distribution curves of the four soils under study were determined. The results are shown in Table 2; Figure 17 shows the distribution curve of three of the soils.

Table 2 - PARTICLE SIZE DISTRIBUTION - G. T. SAND

DIAMETER (μm)	% PASSING (%)	DIAMETER (μm)	% PASSING (%)
1410.0	90.7	23.0	1.5
1000.0	80.7	13.0	1.5
707.0	65.8	9.3	0.7
500.0	46.6	6.6	0.7
250.0	10.4	5.0	0.7
105.0	2.9	3.5	0.0
75.0	2.6	2.7	0.0
36.0	1.5	1.3	0.0

TABLE 3 - PARTICLE SIZE DISTRIBUTION - ROLLO SAND

DIAMETER (μm)	% PASSING (%)	DIAMETER (μm)	% PASSING (%)
1410.0	86.0	36.4	1.2
1000.0	51.3	23.0	1.2
707.0	12.8	13.3	1.2
500.0	4.5	9.4	1.2
250.0	1.3	6.7	0.6
105.0	1.1	4.7	0.6
75.0	1.1	3.4	0.0

TABLE 4 - PARTICLE SIZE DISTRIBUTION - SRP #1

DIAMETER (μm)	% PASSING (%)	DIAMETER (μm)	% PASSING (%)
1410.0	97.1	7.6	30.4
1000.0	94.5	5.4	29.7
500.0	80.4	3.8	29.7
250.0	61.0	2.7	29.0
75.0	34.8	2.0	28.3
63.0	34.2	1.1	27.7
29.0	33.1	1.0	27.0
18.4	32.4	0.8	26.3
10.7	31.7	0.7	25.6

TABLE 5 - PARTICLE SIZE DISTRIBUTION - SRP #2

DIAMETER (μm)	% PASSING (%)	DIAMETER (μm)	% PASSING (%)
1410.0	97.1	16.5	42.3
1000.0	94.6	9.6	41.6
500.0	84.2	6.9	40.9
250.0	62.1	4.9	40.3
75.0	43.3	2.4	39.6
63.0	43.1	1.0	38.9
25.8	43.0		

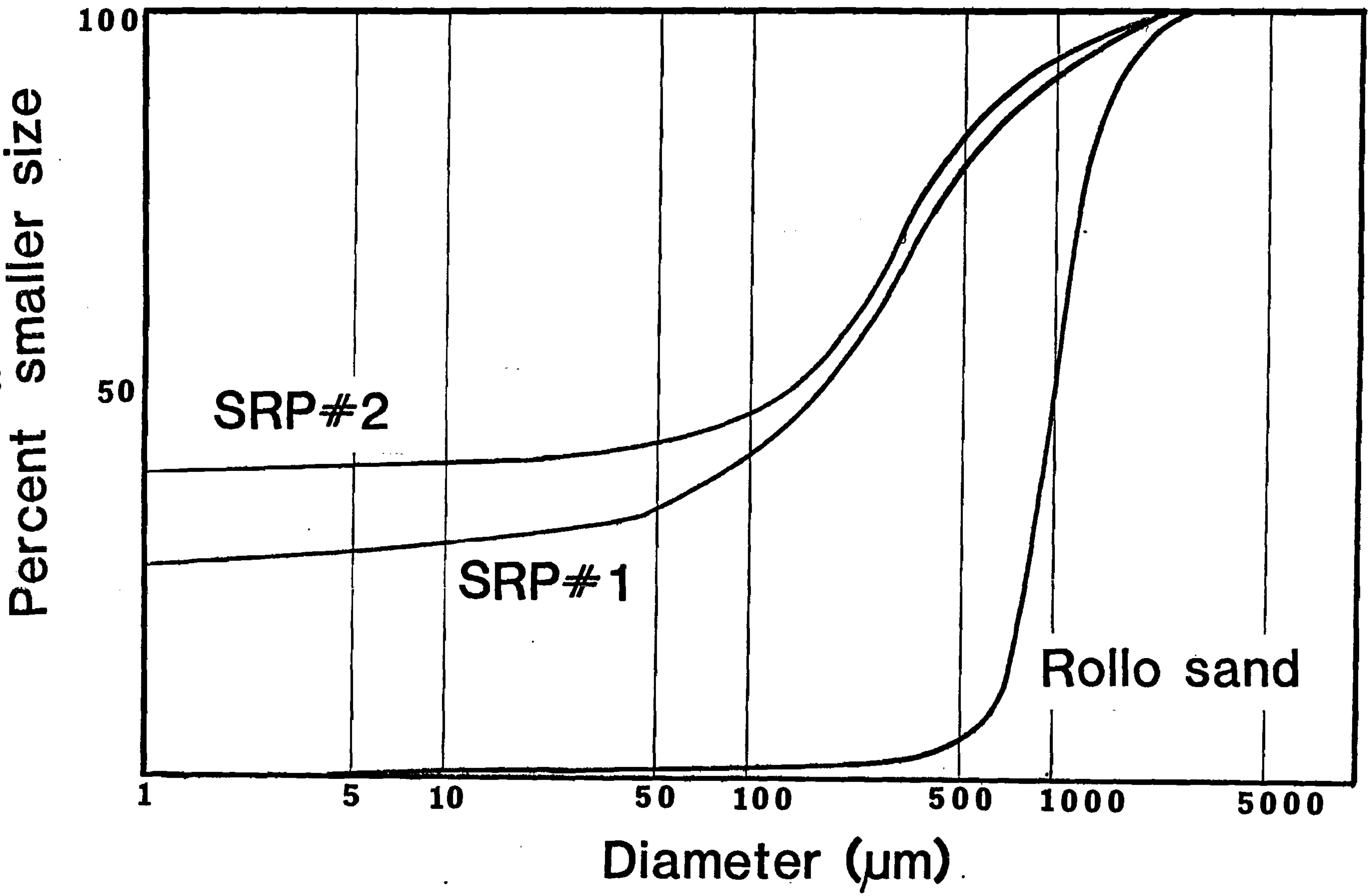


Figure 17 Particle size distributions

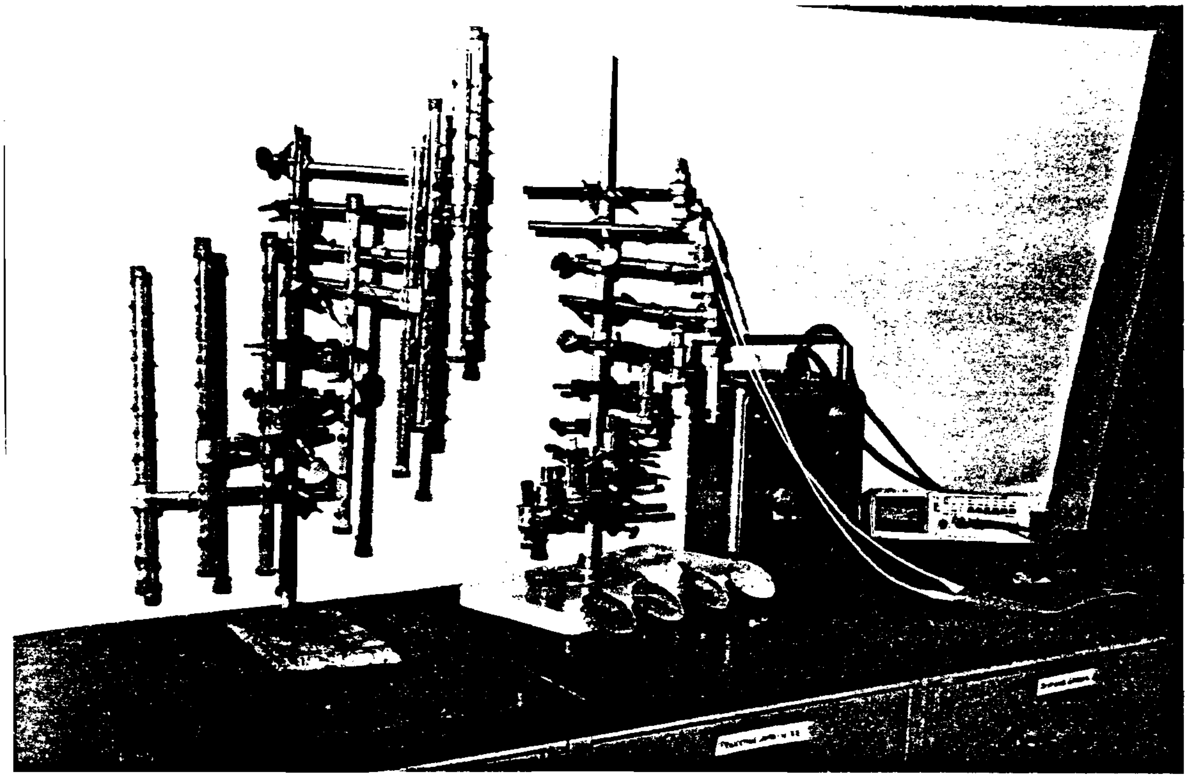
LABORATORY TESTS

Bench-scale tests were conducted to evaluate the basic properties of the soils, to measure residual moisture levels and to calibrate the conductivity probes for use in the test bed. Column tests were conducted in three sizes of tubes, which are shown in Figure 18. The short tubes, top right were employed mainly to obtain residual moisture contents, though care had to be taken to allow for the suction layer above the bottom screens. The other columns had built-in electrodes and were calibrated by direct weight-loss moisture determinations. The larger columns, Fig 18c, have been used for hydraulic conductivity measurements and for radiotracer tests.

Figures 19-21 present electrode calibration curves, plotting electric resistance between adjoining electrodes versus percent saturation, for GT sand and the two SRP soil samples. For consistent results, care had to be taken to ensure even packing and the column had to be presaturated to remove any remaining air. The calibrations for the various columns were consistent, but in practice the electrodes had to be recalibrated for the large test bed.

Since the purpose of the project was to minimize soil water content surrounding the waste material, it was important to measure how low a moisture content could be obtained by draining. Due to capillarity effects all soils will retain a minimum moisture content once water has infiltrated, with the amount retained dependent on pore size, surface wetability and clay content.

Table 6 shows the results of a series of tests on sized sand columns. As expected, the finer sizes (large mesh number) retain more water in their smaller pores. Table 7 compares the residual water content for two sands and two SRP soils, whose size distribution was shown in Figure 17. Again, as expected, the SRP soils with their high clay content and fine size components show relatively high residual water values.



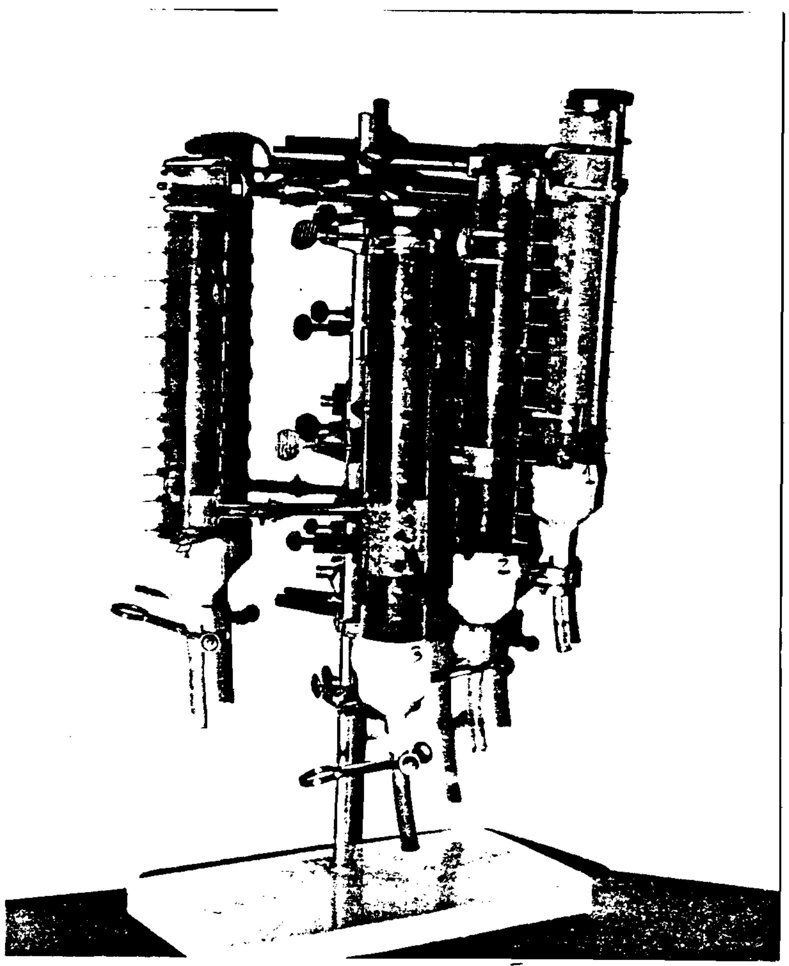


Figure 18 Views of laboratory test columns

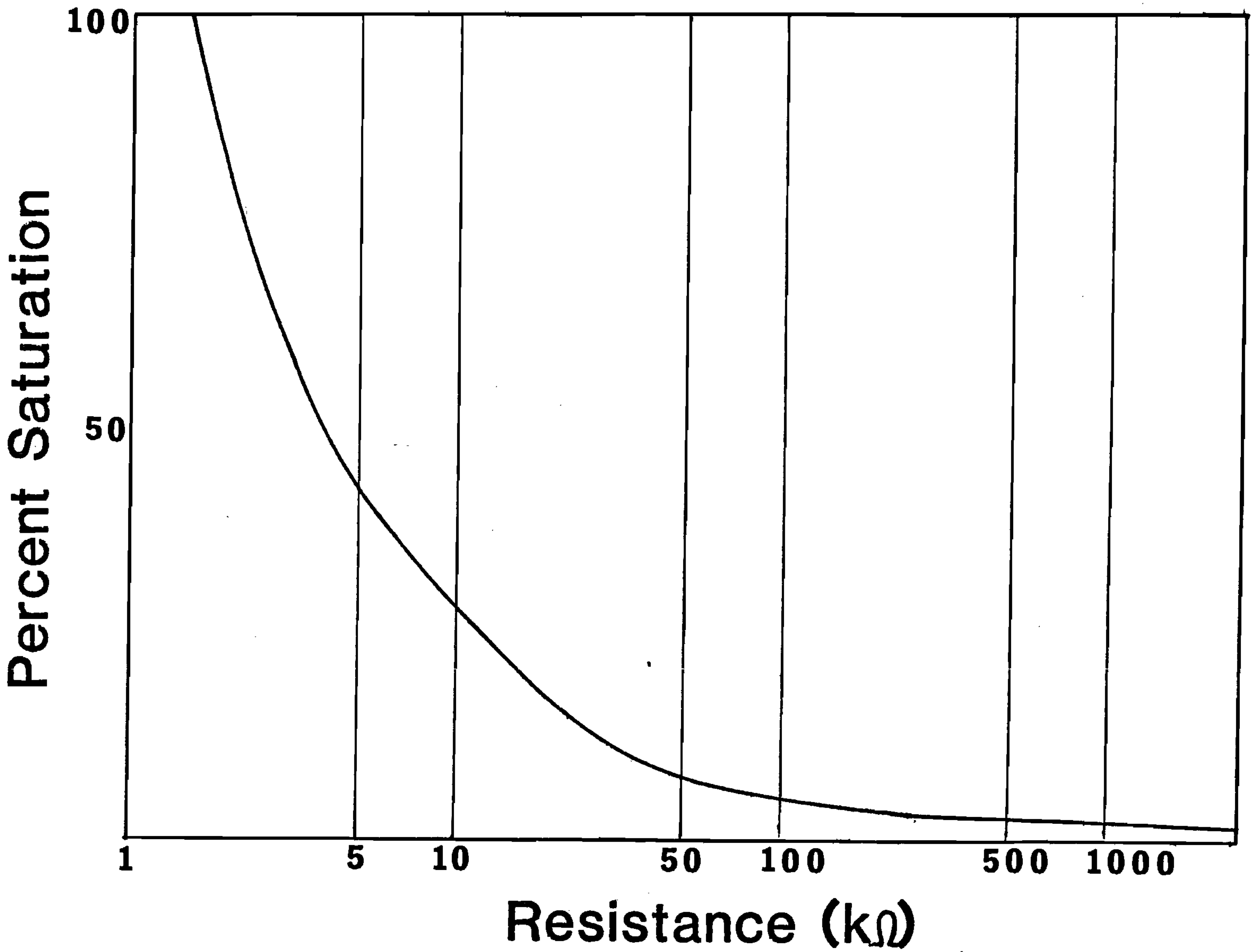


Figure 19 Electrode calibration - GT Sand

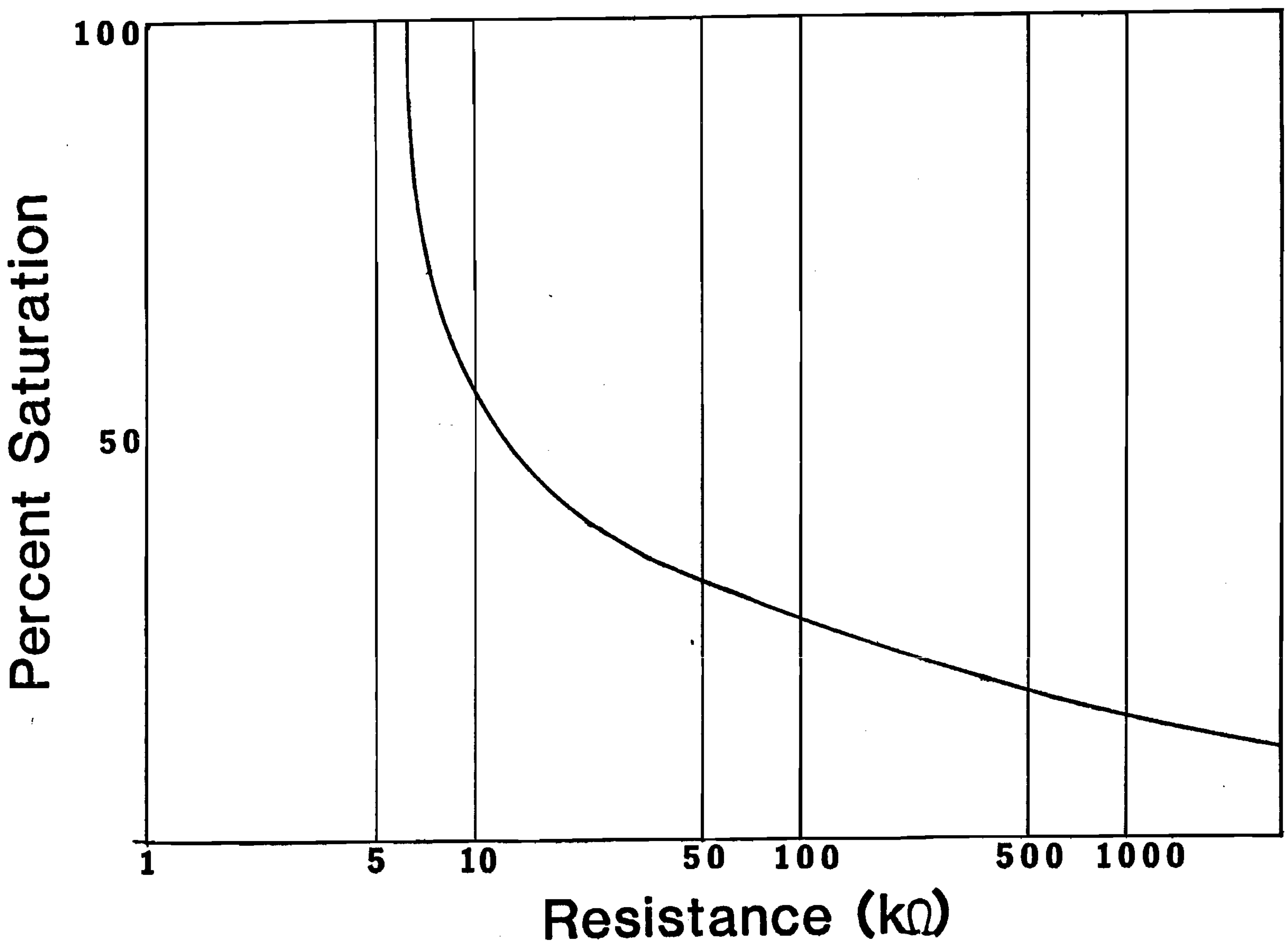


Figure 20 Electrode calibration - SRP # 1 soil

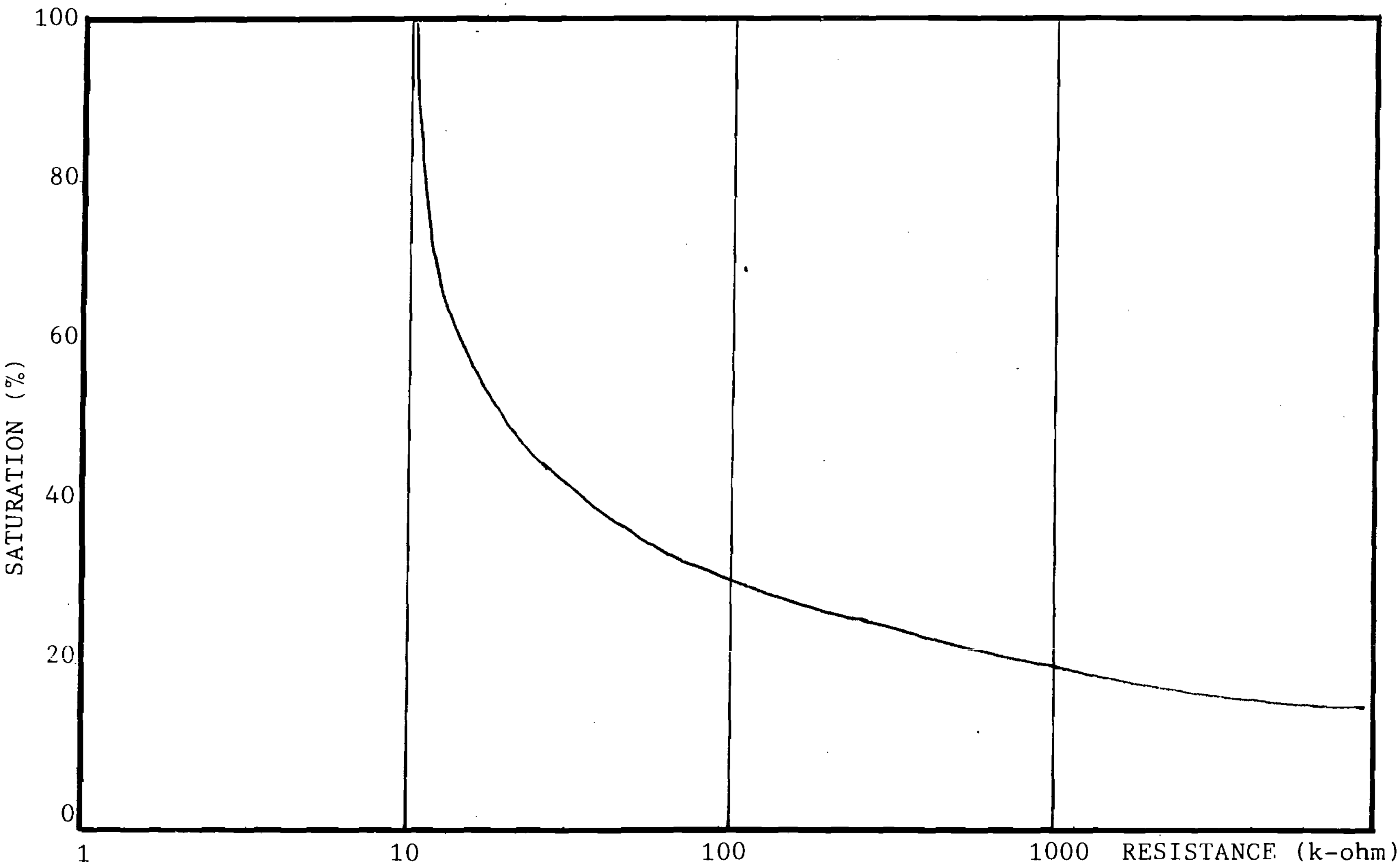


Figure 21 Electrode calibration - SRP # 2 soil

TABLE 6 - RESIDUAL WATER CONTENT FOR SIZED SAND SAMPLES

MESH SIZE	RESIDUAL WATER CONTENT (%)
14-16	0.05
16-20	0.16
25-30	0.18
30-55	0.25
40-50	0.33
50-60	0.61

TABLE 7 - RESIDUAL WATER CONTENT

SOIL TYPE	RESIDUAL WATER CONTENT
Rollo Sand	0.89%
G. T. Sand	1.59
SRP #1	10.51
SRP #2	17.37

One of the consequences of the capillarity effect, also, is the retention of moisture due to surface tension at any major interface. This applies particularly whenever a dense soil layer lies above a cavity, such as a waste volume or a gravel bed. If the interface is sloped, this effect can lead to substantial lateral waste movement. Table 8 records measurements of the wet layers at the open bottom ends of the columns. For the SRP soils this retained wet layer was substantial and even after 30 days there was some continued water loss.

Similar observations have been carried out on the test bed for Rollo sand, GT sand and FP soil. The observed minimum wet base layers were found to be 15cm high for the GT sand and about 30cm for the FP soil.

TABLE 8 - RESIDUAL WET LAYERS AT OPEN ENDS (30 DAYS)

MATERIAL	3CM COLUMN	1.2 CM COLUMN
Rollo Sand	2cm	2cm
G. T. Sand	8	2
SRP #1	14	2
SRP #2	16	2

TEST BED EXPERIMENTS

Use of the test bed had to be planned carefully, if only because the amount of material needed to fill it represented about two cubic yards or about half a ton of soil material, which had to be carefully screened and prepared. Since the tensiometers proved to be insufficiently responsive to rapid changes, most moisture profiles were obtained with the use of electric conductivity probes, which had to be carefully installed and calibrated. An early problem with a floating electric ground potential was overcome by careful grounding of the measuring unit.

The principal purpose of the test bed experiments has been the collection of data of drainage rates, residual moisture, bed support performance and response to cyclic infiltration. At this time work on the latter effect is only beginning and no definite results can be reported.

Among the most interesting results are a succession of drainage curves of which Fig. 22 is a representative sample. It shows moisture measurements at three levels in the box, 19, 94 and 144 cm. from the top, following saturation loading, in Rollo sand. Drainage is very rapid in this medium and at the 144 cm. level a distinct knee appears demarking the transition from the gravitational regime to the tension regime. Fig. 23 shows the resolution of that curve into two exponential rates from which the appropriate rate constants can be derived. These constants in turn can be inserted into the flow model to determine the time variation in the water content following a step increase in water inflow.

Another type of observation represents the moisture profile for a given water content in the column. Fig. 24 shows a typical profile observed in the test bed. These results have been correlated with calculations of an unsaturated flow model for a cylindrical system. This program can generate moisture contours that are critically dependent on the relative magnitude of the gravitational and the tension drainage coefficients.

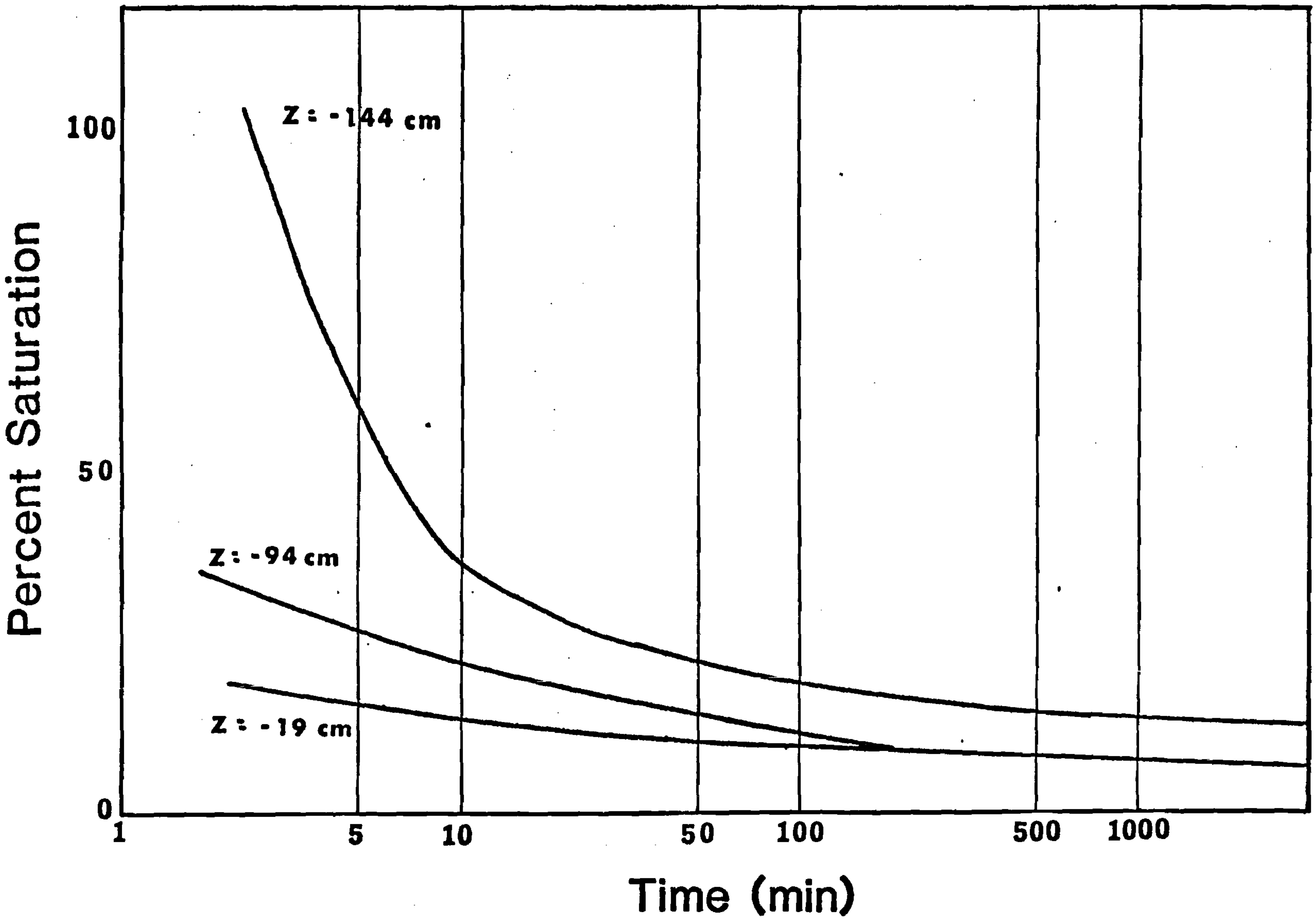


Figure 22 Drainage curves - Rollo Sand

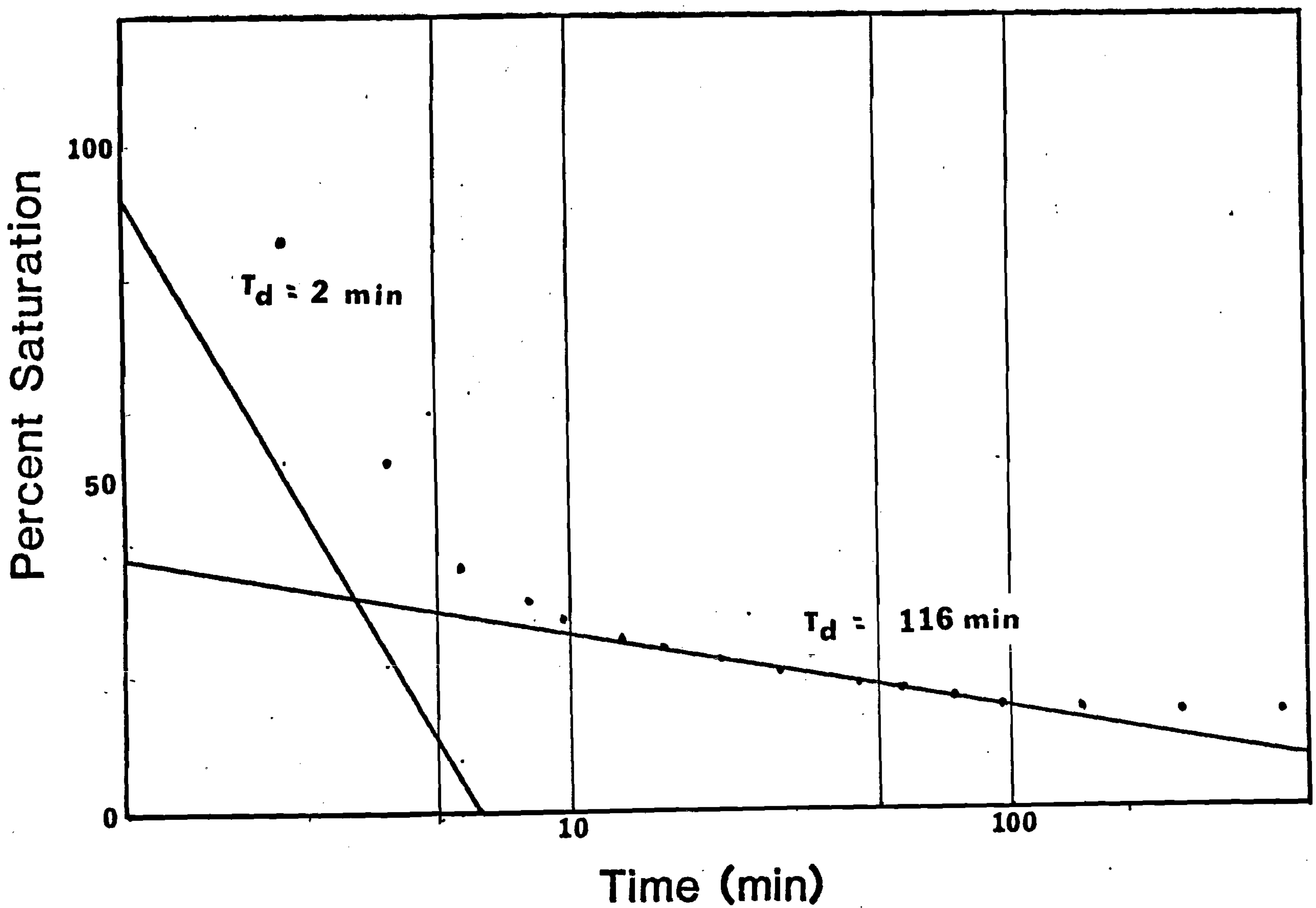


Figure 23 Resolved drainage curve - Rollo Sand

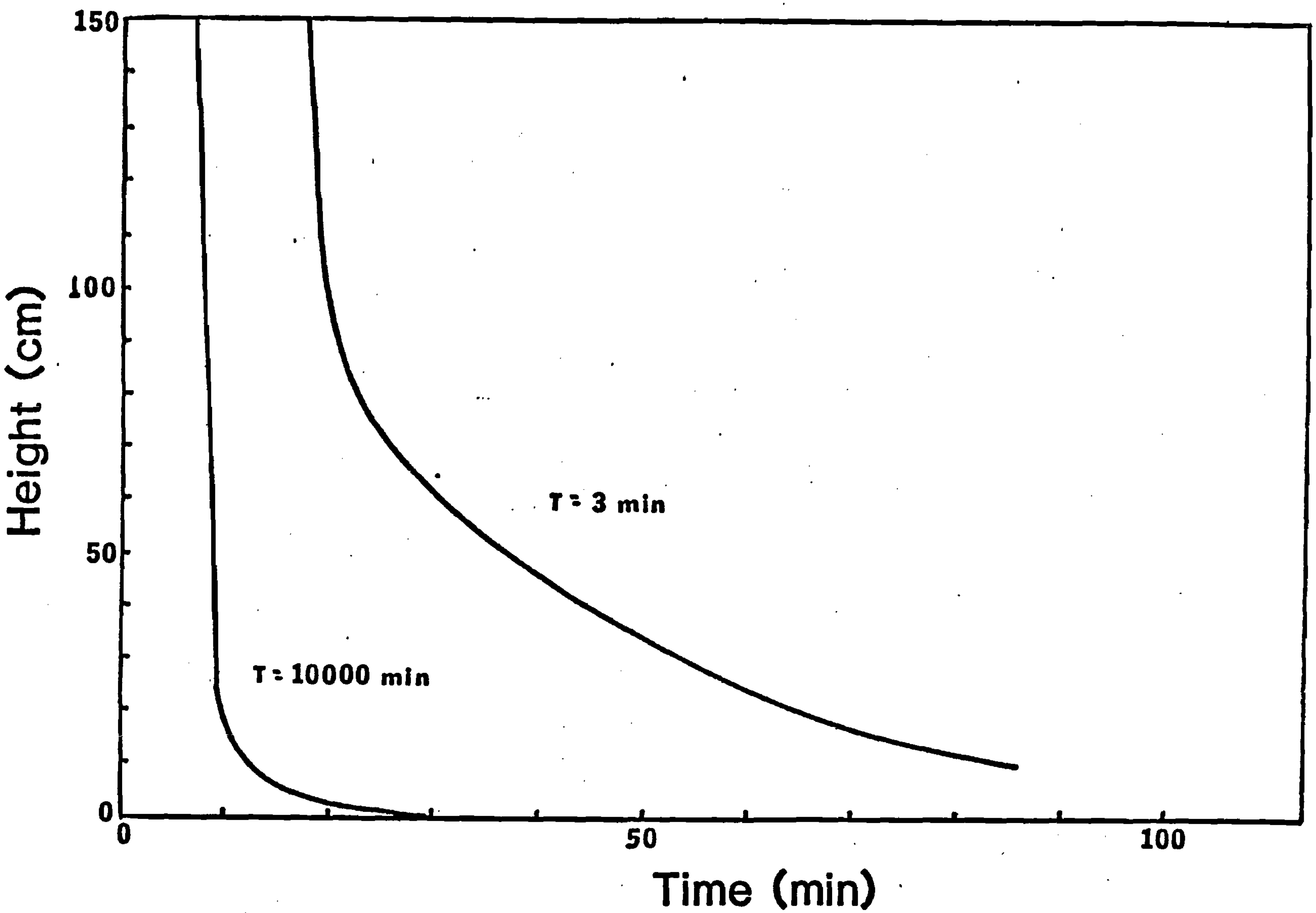


Figure 24 Moisture Profiles - Rollo Sand

Figure 25 shows the moisture profile for GT SAND plotted against the height above the drain. The curve on the right shows the profile at one minute after drainage begins. The middle curve describes the profile after 30 minutes of drainage. The curve on the left shows the moisture profile after 8800 minutes of drainage (about 6 days). The moisture content is seen to be uniform at a height greater than 20 cm above the drain. There is an interface between the soil at residual moisture content (11% of saturation) and the more saturated (75%) soil directly above the drain. Groups of electrodes were placed at 10 cm intervals inside the lysimeter. We cannot determine the exact location of the interface; it lies between 10 cm and 20 cm above the drain. Figure 25 clearly shows that in an unsaturated soil areas of higher saturation can be generated by changes in the soil properties.

Figure 26 is the moisture profile for FP SOIL. The curves compare the moisture profiles at two different times. The curves show the interface between the wet soil and the soil at residual moisture content occurring at a height of between 30 cm and 40 cm. The residual water content of the FP SOIL is estimated to be approximately 30 percent of saturation.

Figure 27 are the drainage curves for GT SAND at different heights above the drain. The lower curve describes the percent saturation as a function of time for the top of the soil column, 50 cm above the drain and 10 cm below the soil surface. This curve illustrates the initial rapid drainage of the soil followed by a slower decline to the residual moisture content. The upper curve reveals the moisture content at the bottom of the lysimeter, 10 cm above the drain. The graph shows a long plateau where the moisture content at the bottom is nearly constant while the upper portions of the column are draining. It is thought that the infiltration into this zone from above occurs at the same rate as the drainage into the gravel, thereby keeping the moisture content constant. As the upper region approaches the residual moisture content, the downward flow of water slows and the lower area begins to drain.

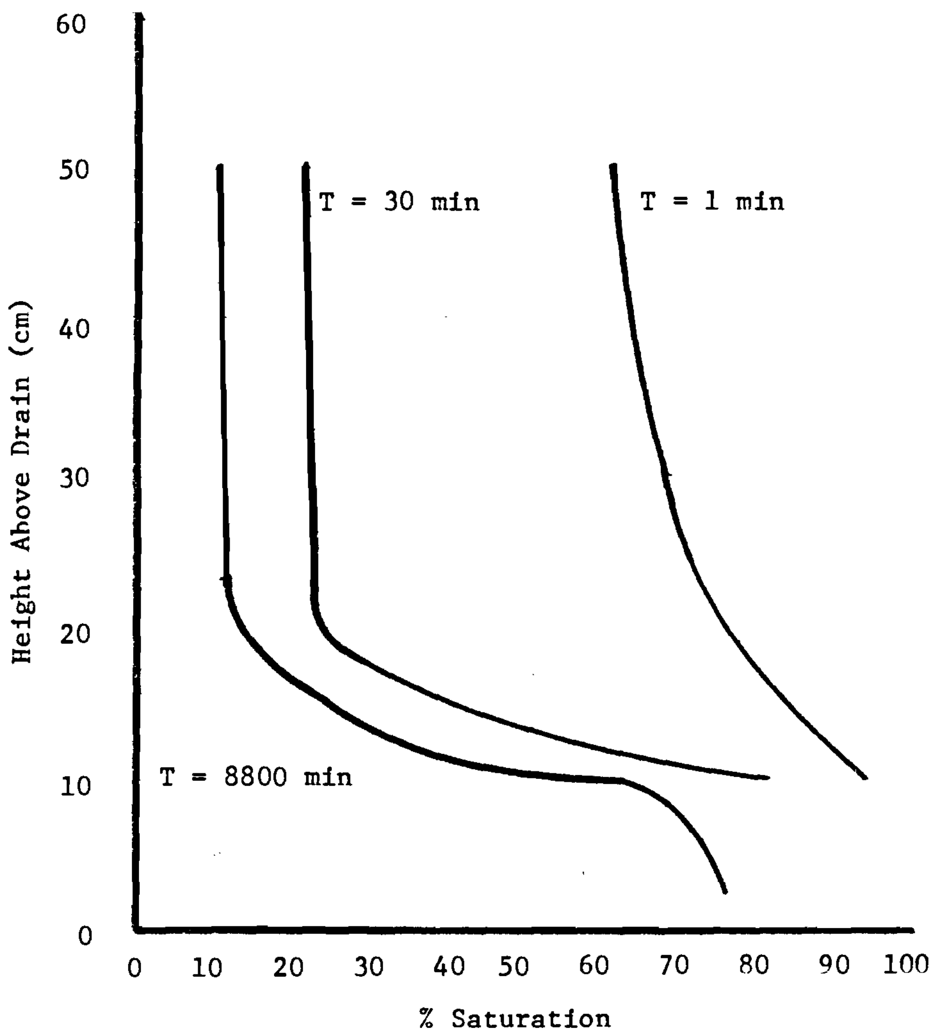


Figure 25 Moisture Profiles for GT Sand at different times

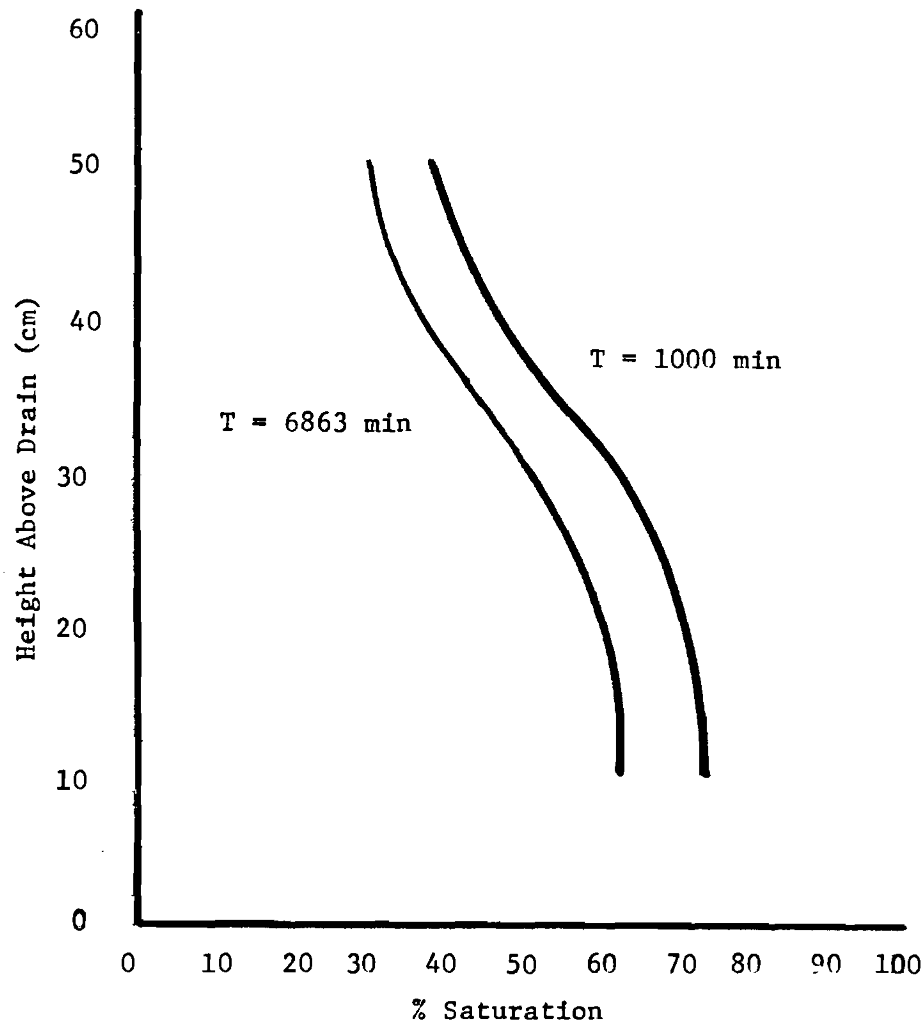


Figure 26 Moisture Profiles for FP Soil at different times

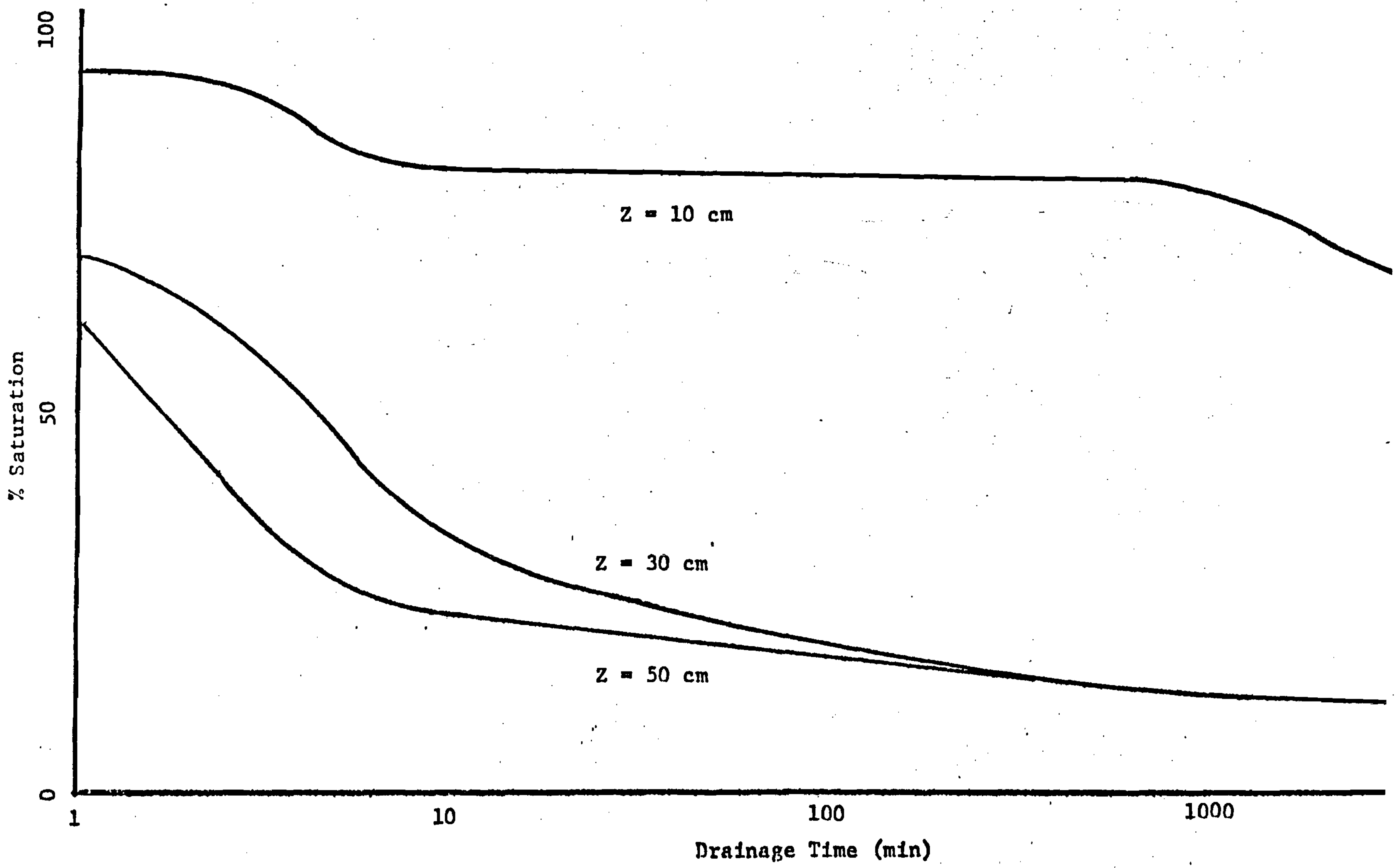


Figure 27 Drainage Curves for GT Sand at different heights

It can be seen from the figure that the drainage from a high percent saturation to a low percent saturation occurs very rapidly in GT SAND. It takes 10 minutes to go from 70 percent of saturation to 30%. The soil returns to its residual moisture content within 1440 minutes (24 hours). If precipitation occurs less than daily, the soil will drain between infiltrations.

Figure 28 are the drainage curves for FP SOIL at different heights above the drain. The curves are of the same general type as the GT SAND drainage curves. The dotted region between 10 and 150 minutes indicates that the system had not reached equilibrium before the start of the drainage test.

Water was ponded over the soil surface for one hour prior to the start. The Z = 10 cm curve clearly shows the rise from residual moisture content to about 64% of saturation. The residual moisture content of the FP SOIL is about 30% of saturation. This value is reached in approximately 4000 minutes (3 days).

Figure 29 is a comparison of the drainage curves for the three soils. The two sands have similar curves. There is an initial region of rapid drainage followed by a couple of hours of slower drainage. The sands have attained residual moisture content in less than five hours. Rollo Sand and GT SAND have residual moisture contents of 12 and 10 percent of saturation respectively. The FP SOIL, with its significant clay fraction, requires an order of magnitude more time to reach its residual moisture content. The measurements used in Figure 26 were taken 10 cm below the surface.

Figure 30 shows the drainage curves for Rollo Sand and GT Sand resolved into their component parts. The curves are percent of saturation plotted against log time. Both sands show a two-part drainage curve. The initial portion is presumably the gravity drainage of the larger pores and is significant for the first 10 minutes. The second component continues to drain for several hours until residual moisture content is reached. Rollo

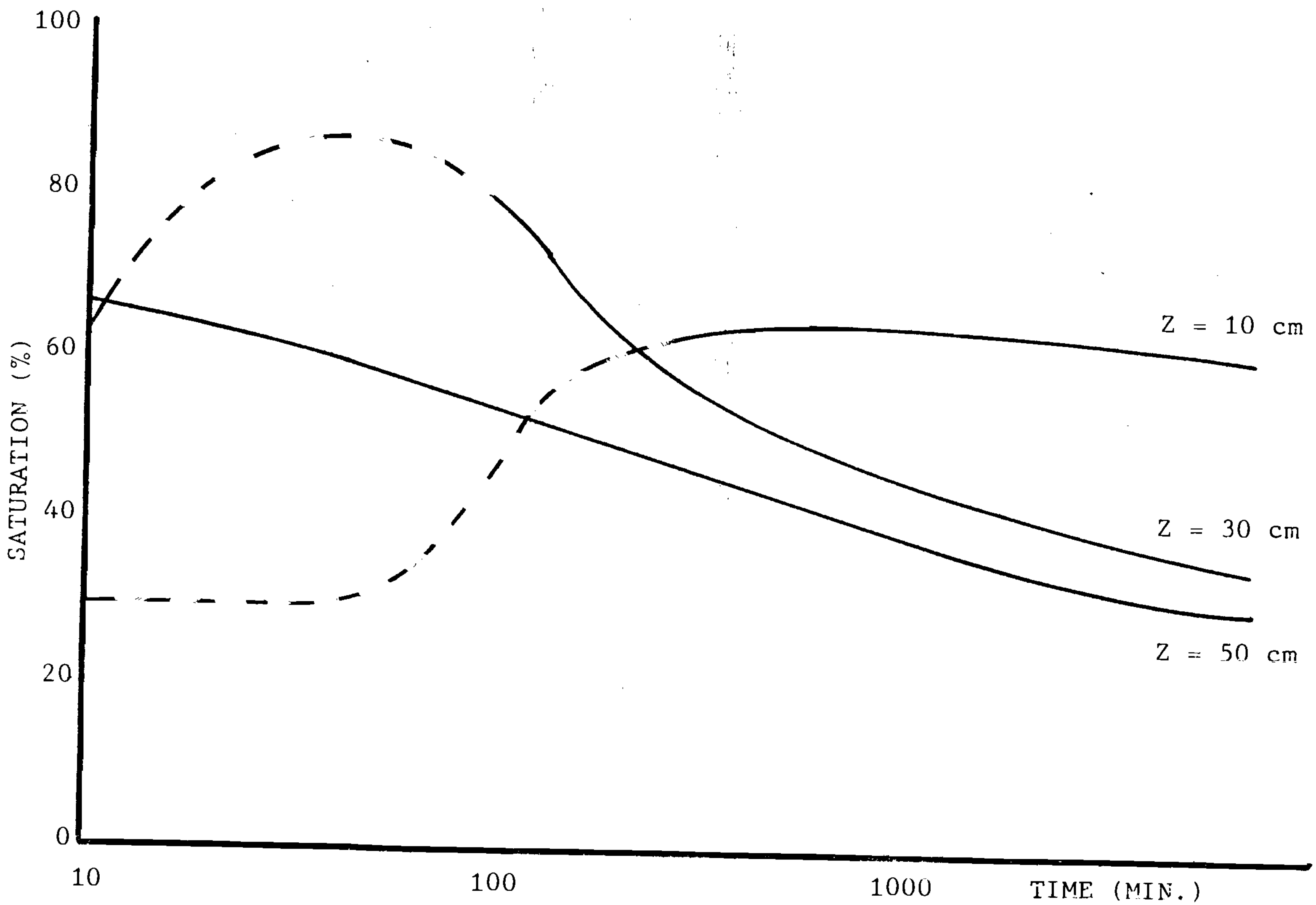


Figure 28 Drainage curves for FP Soil at different times

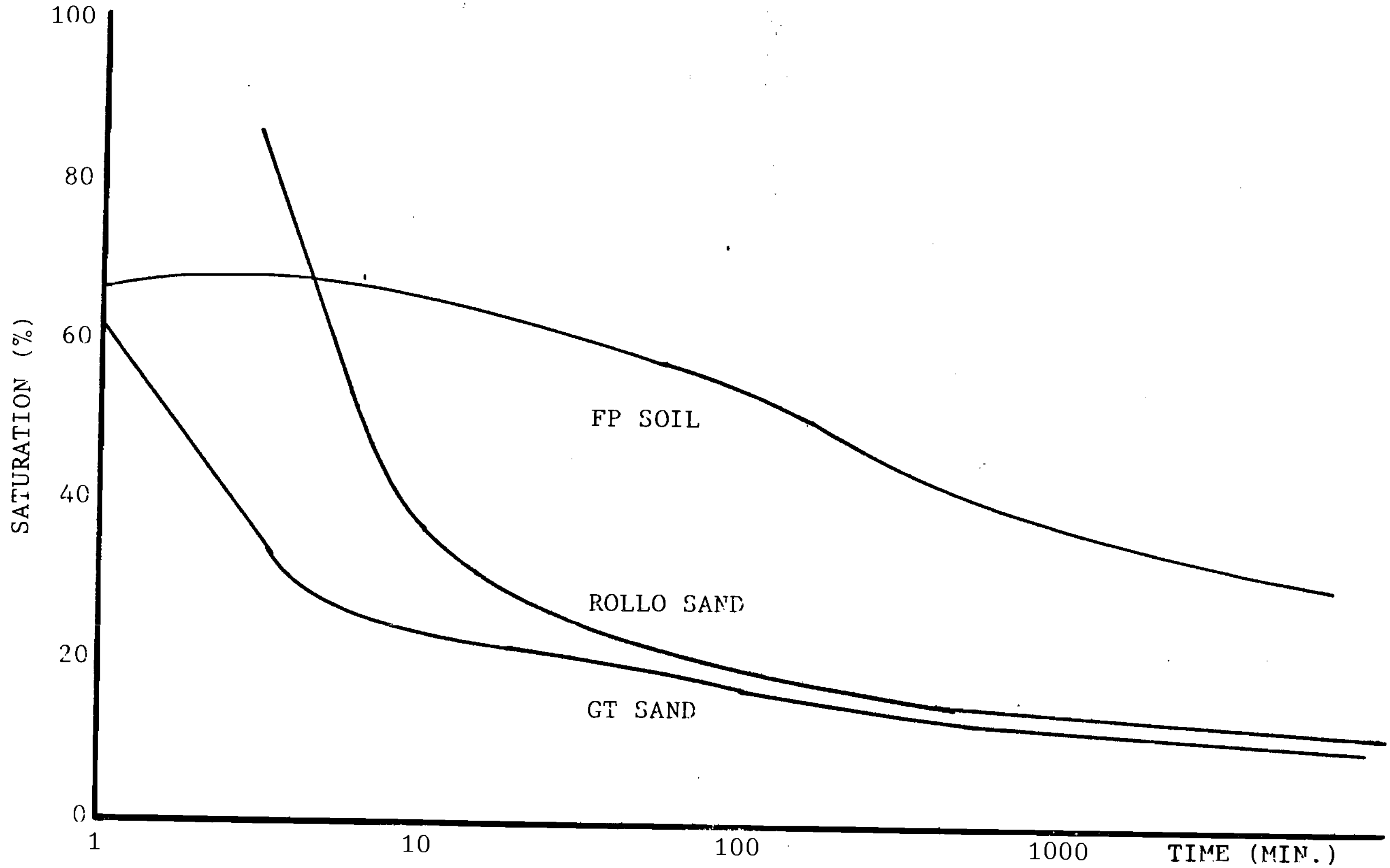


Figure 29 Drainage Curves for three soil types

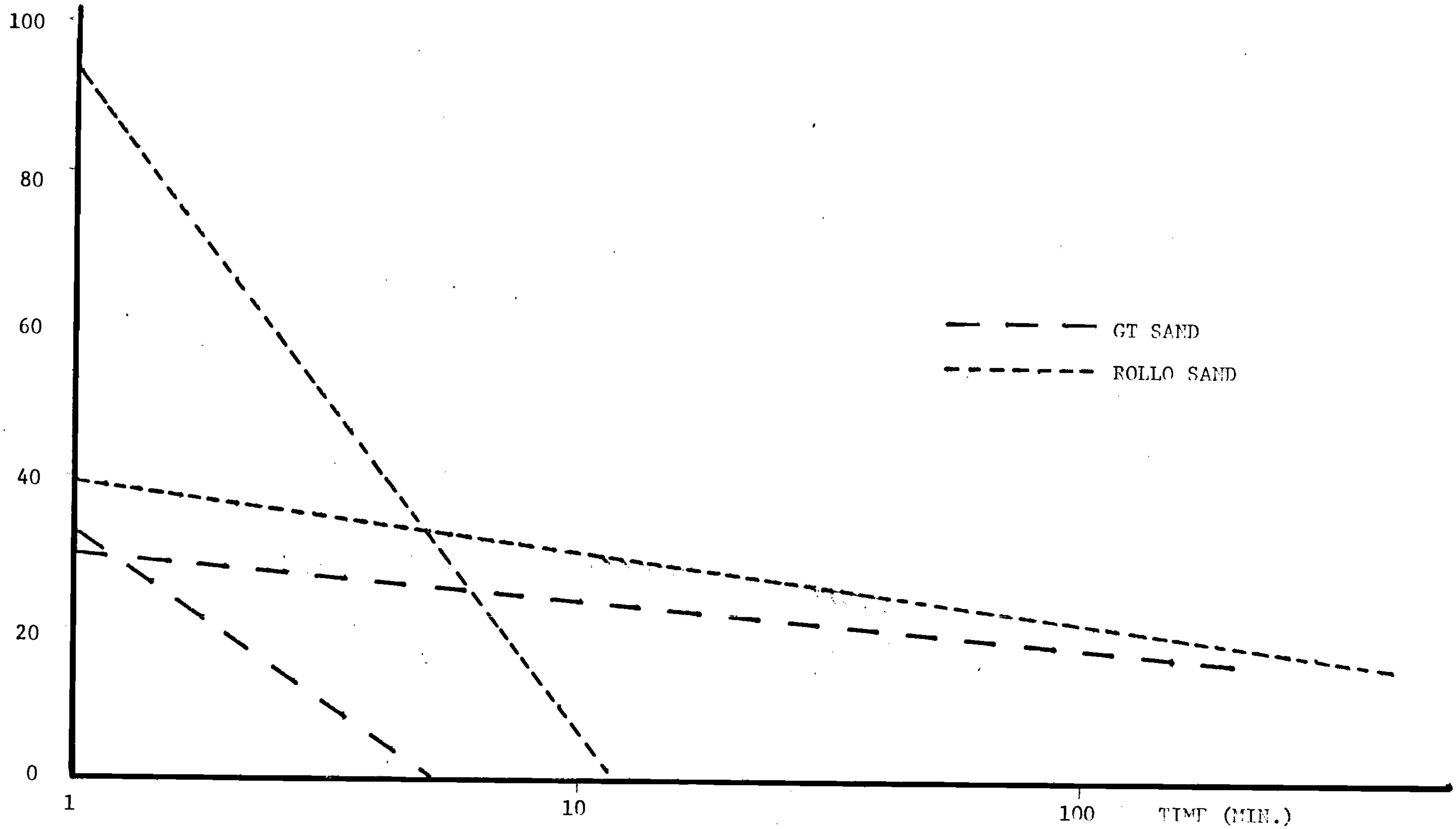


Figure 30 Resolved Drainage Curves for two sands

Sand is shown to drain faster, which is to be expected, due to its large, uniform sized particles. It is interesting to note that the time of drainage is a function of the percent saturation. The drainage equation can be expressed as:

$$T = C \quad e^{-(k \quad s)}$$

where T is the drainage time, C is an empirical constant, k is the drainage constant and s is the percent saturation.

Rollo Sand was found to have drainage constants of 0.247 s^{-1} and 0.0266 s^{-1} for the rapid and slow drainage respectively. GT Sand has k's of 0.384 s^{-1}. The initial drainage rates are only significant in the first five to ten minutes. It must be remembered that these values are calculated for the top 10 cm of the soil column. The curves become more complex with depth due to the variable infiltration of moisture from above.

A drainage curve resolution was not done for the FP Soil. The soil had not achieved its equilibrium conditions due to a insufficient initial infiltration time. The experiment is being repeated using a much longer infiltration time.

Calibration fo the electrodes was done in the field by taking a soil sample from between each electrode pair. The water content was determined gravimetrically. The bulk density and porosity were also determined under field conditions.

An important feature of a well-drained bed is the retained moisture at the bottom of the column. In the test bed, the sand layers were supported by a mesh screen that was placed on top of the coarse gravel bed which provided the drainage path. In sand, ordinarily, little moisture should be retained due to surface tension effects at the lower surface. However, it was found that the wire mesh supported a film of water of sufficient strength to maintain significant moisture in the sandbed up to a height of about 14 cm. Proper choice of the supporting material is obviously important to minimize this effect, while yet retaining the bed material sufficiently to avoid clogging of the gravel layer. In practice it is felt that a graded gravel layer can supply enough support for the soil and may be preferable to a screen or open-mesh liner material.

Since the usefulness of the drainage layer could be impaired by silting over a long period, qualitative observations were maintained on silt infiltration into the gravel bed. It was found that a little fine silt material was washed into the gravel in the early stages of the test, but later, with the readily mobile material removed from the bottom soil layer, no further silt movement seemed to occur.

WASTE LEACHING IN UNSATURATED CONDITIONS

One of the principal objectives of this work is the reduction in the source term from water attack on the waste material by reduction of the quantity of water in contact with the waste and the time available for migration processes. For vitrified waste, Pescatore and Machiels (23) have argued that for slow flow rates the diffusion rate of waste ions to the surface layer becomes the rate-determining step. Most waste depository models assume that water flow is continuous, saturated and that the leach rate is proportional to flow rate at a constant solubility. Under unsaturated flow conditions or cyclic flow conditions, it is not at all clear if leaching occurs in a constant fashion and whether it is necessarily proportional to volumetric flow rate. Test work is under way with simulated waste to study these processes, but the results are inconclusive so far, partly because of slow leaching rates and partly because of the need to employ equilibrated water for reasonable simulation, whose composition is, to some extent, affected by the nature of the simulated waste itself. Similar considerations affect the leachability and migration rates of other waste trench simulations, such as the SRP lysimeter tests (15), where flow also is unsaturated much of the time.

The test work conducted in the laboratory has been of two types, recirculating water through simulated waste material and once-through flow tests. The simulated waste consisted on ion exchange resins labeled with Cs-137 or Tc-99m. This material was chosen, because it was felt that other waste forms either would be too insoluble to result in statistically valid desorption or would be too inhomogeneous for comparison. The recirculated tests suffered from constant change in pH due to the effect of the waste resin and those tests were not pursued. Once-through flow tests with equilibrated water were more controllable, but have resulted in too low a level of desorption to be usable so far; these tests are continuing and it is hoped to place them on a more productive basis.

In the meantime, for calculational purposes it is assumed that the leach rate is proportional to the time-integrated volumetric flow. That is a problematic assumption, because of the diffusion rate and concentration-gradient dependence of the leach process which makes it improbable that the leach source term is proportional to water volume under pulsed conditions. However, for the moment that assumption seems the best available.

COMPUTER SIMULATION

To evaluate the effects of unsaturated flow under time-dependent conditions, a one-dimensional computer program has been developed. This program can describe pulse flow conditions in the test bed and the movement of the moisture profile. Details of the program are presented in Appendix A.

The results depend, of course, on the relative magnitude of the pressure head (gravitational force) and the suction head (capillarity). Figures 31 and 32 illustrates two cases where their relative magnitudes vary.

The general features of computer model for this facility are shown in Figure 33. On the left are the physical processes involved, on the right the various rate processes that determine waste migration from the source.

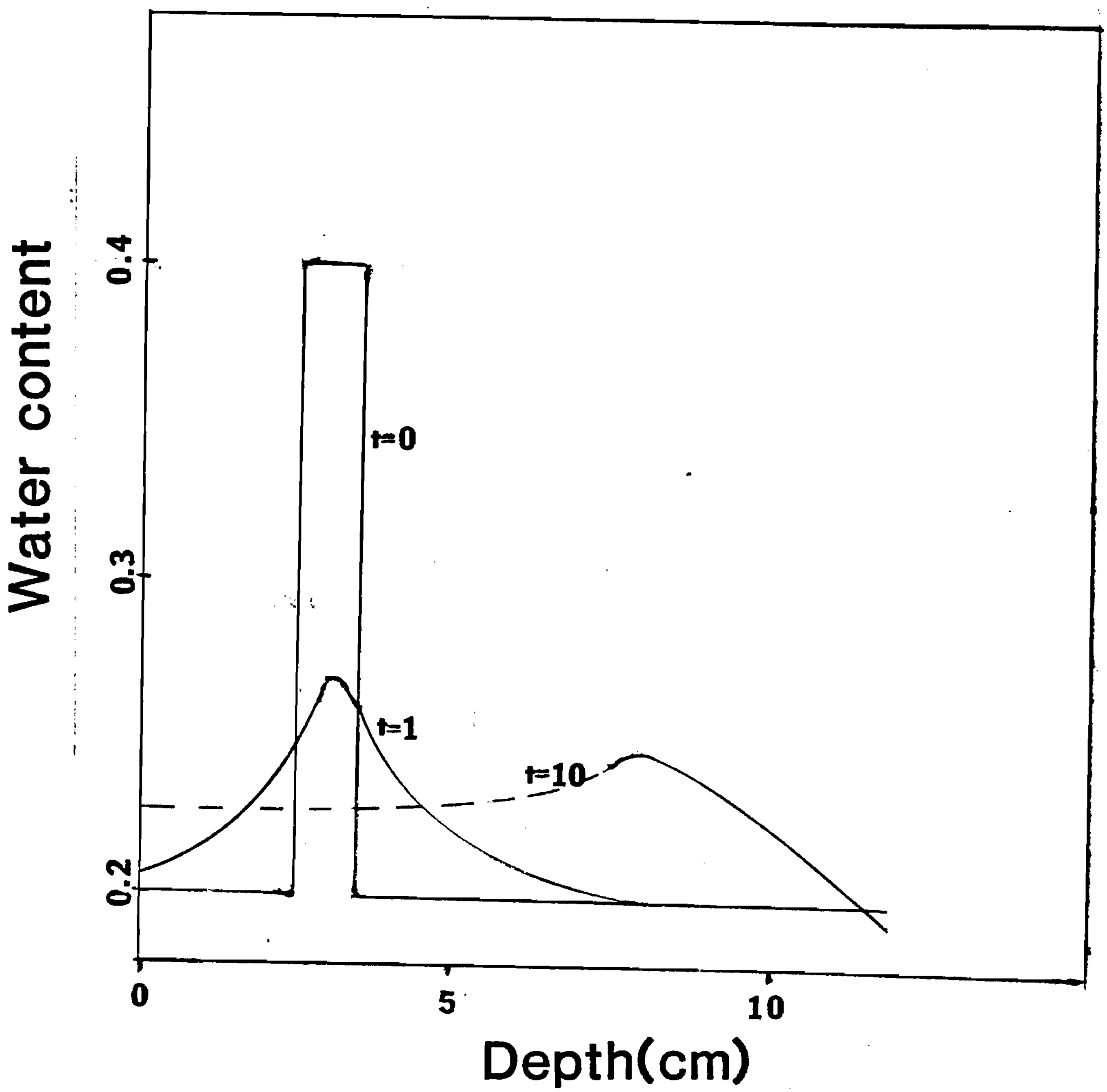


Figure 31 Calculated Moisture Profiles - Comparable forces

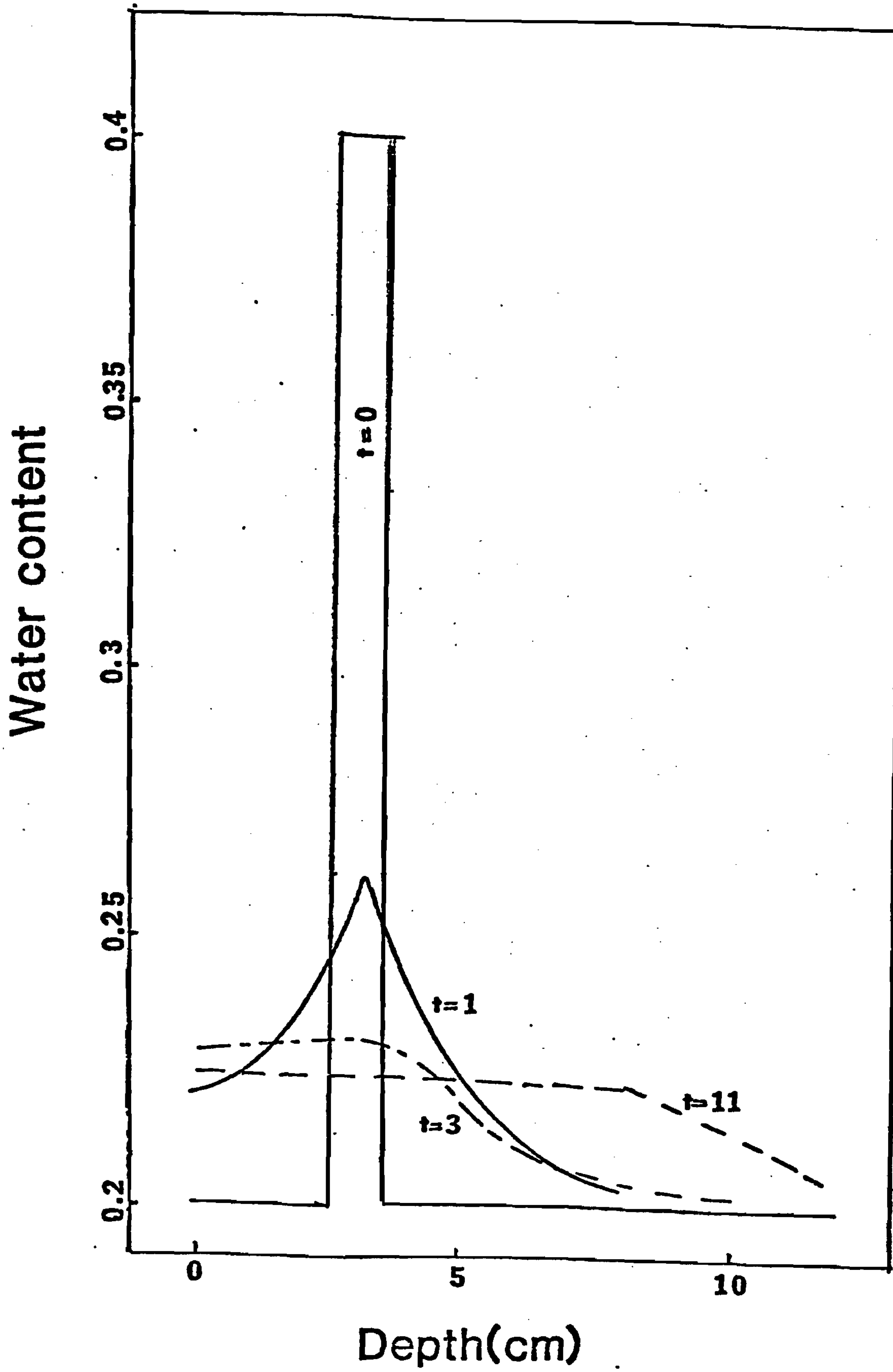


Figure 32 Calculated Moisture Profiles - Suction dominant

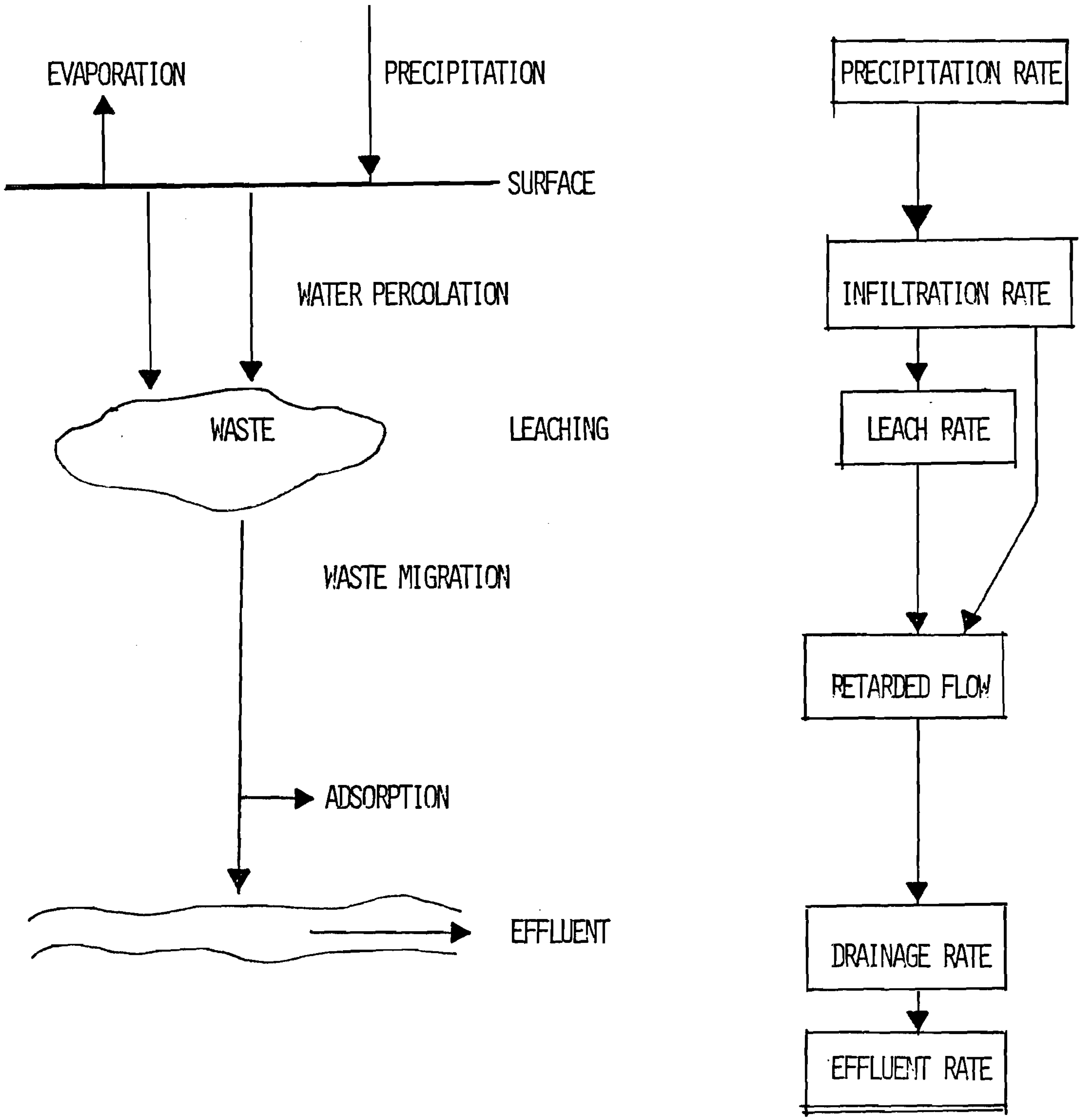


Figure 33 Diagram of Migration Model

Details of the model development go beyond the scope of this report and will be available shortly in extended form (de Sousa, Ph.D Thesis, 1985). The program description is attached in Appendix A - C. The model is based on a finite element technique which was used to solve the one-dimensional unsaturated flow and transport equations. Boundary conditions include provision for a Neumann variable flux condition, so as to represent a seepage boundary, as well as a Dirichlet constant boundary condition.

In order to use the water flow and transport model to simulate a shallow land burial site performance, it is necessary to determine how well can the model simulate the unsaturated regime present in the soils. Since the transport model uses the results obtained with the flow model, the latter was the first one to be checked.

Flow model

The first simulation done to check the accuracy of the water flow model corresponded to the situation in which an homogeneous saturated column of soil was submitted to a constant infiltration equal to the saturated hydraulic conductivity of the soil; the boundary condition at the bottom of the column corresponded to a free draining profile. In this situation the column should remain saturated, and the pressure head should not change with time, since the infiltration and the drainage rates are equal; the results obtained, given in Table 9, showed that the model was simulating correctly that situation. This simulation was useful to the extent that it showed the logic of the model was correct and the matrices were being well assembled and solved.

The ability of the model to reproduce unsaturated flow was checked by simulating the situation presented by Van Genuchten (28) based on the experiments done by Warrick (29). This experiment was chosen because it represents one of the most difficult cases to simulate, which is when a dry soil is subjected to a large infiltration rate.

The experiment consisted of an homogeneous soil column, 125 cm long, which was subjected to the following conditions:

TABLE 9 - FLOW MODEL VERIFICATION

TIME= .050 NL= 1 NT= 1

NNODE	COORDINATE	PRESSURE HEAD
1	.000	-34.460
2	1.000	-34.460
3	2.000	-34.460
4	3.000	-34.460
5	4.000	-34.460
6	5.000	-34.460
7	6.000	-34.460
8	7.000	-34.460
9	8.000	-34.460
10	9.000	-34.460
11	10.000	-34.460
12	11.000	-34.460
13	12.000	-34.460
14	13.000	-34.460

TIME= .125 NL= 1 NT= 2

NNODE	COORDINATE	PRESSURE HEAD
1	.000	-34.460
2	1.000	-34.460
3	2.000	-34.460
4	3.000	-34.460
5	4.000	-34.460
6	5.000	-34.460
7	6.000	-34.460
8	7.000	-34.460
9	8.000	-34.460
10	9.000	-34.460
11	10.000	-34.460
12	11.000	-34.460
13	12.000	-34.460
14	13.000	-34.460

TIME= .225 NL= 1 NT= 3

NNODE	COORDINATE	PRESSURE HEAD
1	.000	-34.460
2	1.000	-34.460
3	2.000	-34.460
4	3.000	-34.460
5	4.000	-34.460
6	5.000	-34.460
7	6.000	-34.460
8	7.000	-34.460
9	8.000	-34.460
10	9.000	-34.460
11	10.000	-34.460
12	11.000	-34.460
13	12.000	-34.460
14	13.000	-34.460

Initial Condition:

$$\theta(x,o) = \begin{cases} 0.15 + 0.0008333 & 0<x\leq 60 \\ 0.20 & 60<x<125 \end{cases} \qquad (1)$$

Boundary Conditions:

$$h(\theta,t) = -14.495 \qquad (2)$$

$$h(125,t) = -159.19 \qquad (3)$$

The water content - hydraulic conductivity and the water content - pressure head relations are given by:

$$\theta(h)= \begin{cases} 0.6829-0.09524\ \ell n|h| & h\leq -29.484 \\ 0.4531-0.02732\ \ell n|h| & -29.484< h\leq -14.495 \end{cases} \qquad (4)$$

$$k(h)= \begin{cases} 19.34\text{x}10^5\ |h|^{-3.4095} & h\leq -29.484 \\ 516.8\ |h|^{-0.97814} & -29.484< h\leq -14.495 \end{cases} \qquad (5)$$

The flow model is written in terms of pressure head and so the initial pressure head distribution is given by substituting eq.1 in eq. 4; the boundary condition at the surface (eq. 2) implies that the soil is maintained saturated at the top of the column at all times.

The results obtained by using linear finite elements (LFE) and mass lumped linear finite elements (MLFE) are shown in Figure 34. It is seen that in both cases a reasonable simulation is obtained; more accurate results can be obtained if the spatial and time intervals are decreased at the expense of a larger computational time. Another important aspect is that the LFE simulation presents some oscillations at the early stages, and that they decreased as the time increased. These oscillations can be decreased by again decreasing the spatial and time increments. It is then seen that the flow model generates accurate results when used to simulate unsaturated water flow.

The transport model is now being checked, and the same situations used for the flow model will be used to determine if it can be used to simulate the movement of radionuclides through unsaturated soils.

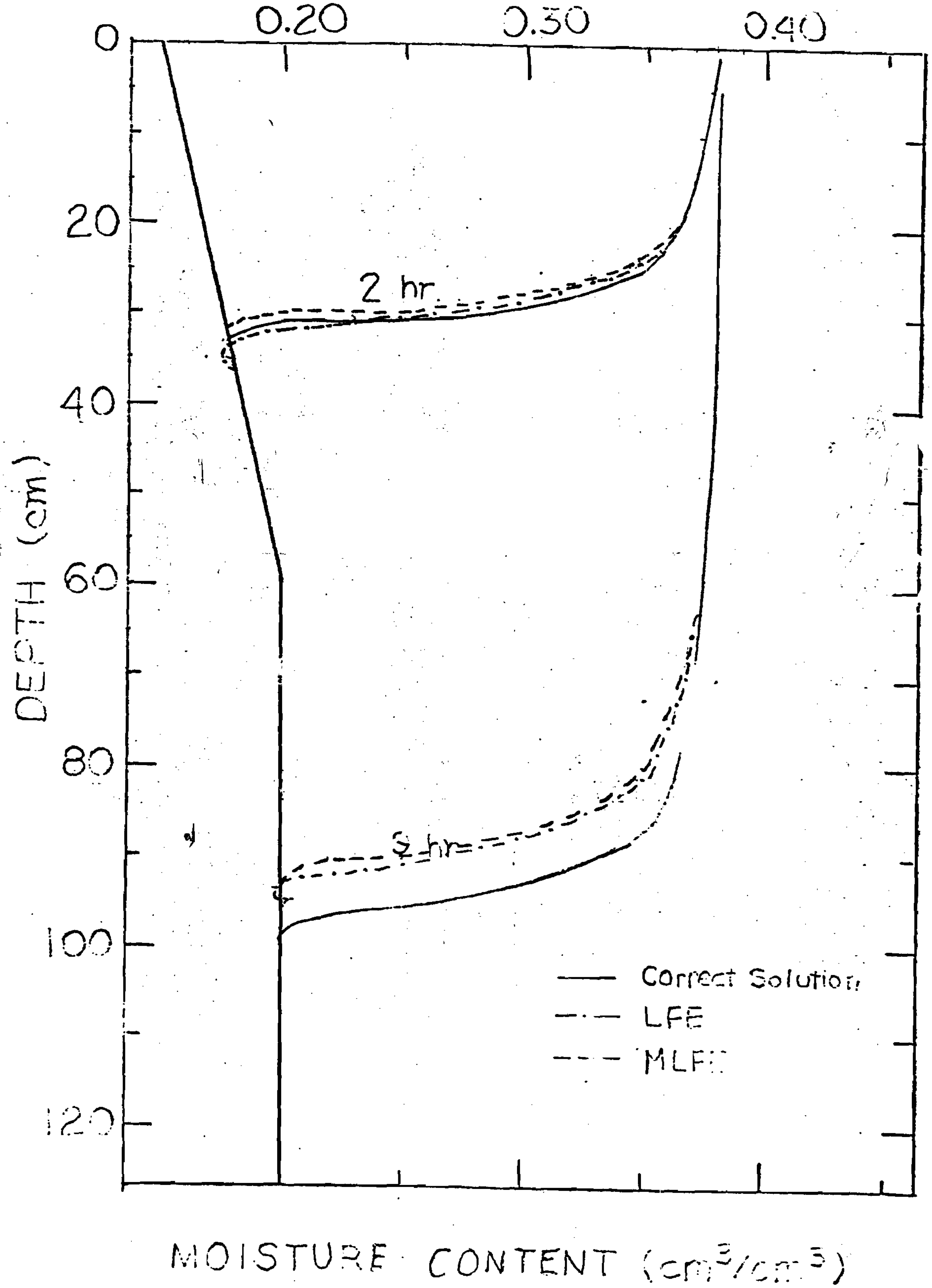


Figure 34 Verification of Flow Model

TRENCH FACILITY DESIGN

The work described above has provided some guides for the design of a facility that is specifically intended to minimize waste leaching by facilitating drainage through the backfill, thus preventing any standing water in the waste volume regardless of the condition of the cap. Since it has been shown that soils with a high clay content retain a substantial amount of moisture at all times, it is evident that a fairly permeable sandy loam would be preferred for the backfill material.

As Table 8 has shown, even for fairly sandy soil there will be a wet layer of up to 12cm above any gravel base; hence waste emplacement should be on top of a soil layer of at least a foot. This will also facilitate waste placement and protect the gravel layer against the action of tracked vehicles in the trench.

Figure 35 is a generalized diagram of the trench design envisaged. (A mesh separator is shown between backfill and gravel bed, but present experience indicates that it is probably unnecessary). The main feature of importance is the gravel bed, which is common to most waste trenches, but assumes a central role in the present design. Given a reasonably permeable backfill soil, it is assumed that following a rainfall most of the infiltrated water will percolate rapidly through the backfill to reach the gravel bed, which must have enough capacity to store this water over a long enough period to permit slow, orderly seepage into the ground without backing up.

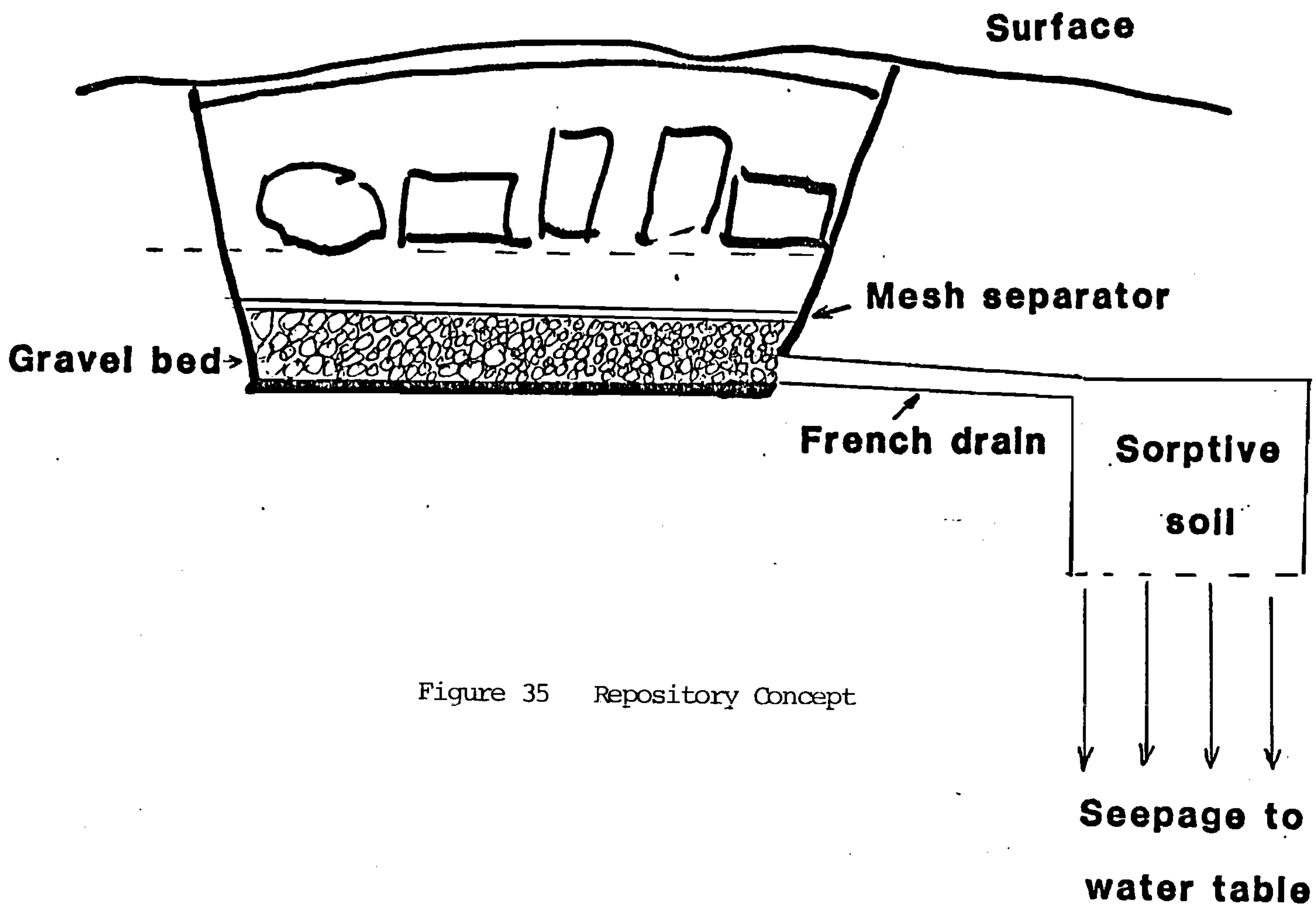


Figure 35 Repository Concept

Calculation of Gravel Reservoir Requirements

The quantity of water that must be accommodated in a near-surface burial site is dependent on three major factors. These are the amount of precipitation, the rate of infiltration of water into the soil, and the rate of movement of the water within the soil. The latter two factors are interrelated, as the limiting factor may be either the rate of passage through the air-soil interface or the rate at which water percolates away from the interface, leaving room for additional water to enter the soil.

The maximum rate at which water can enter the soil under given conditions is called the infiltration capacity. The actual infiltration rate equals the infiltration capacity only when the intensity of rainfall equals or exceeds the infiltration capacity. The infiltration capacity is at its maximum when the soil is dry, but decreases rapidly at the beginning of a storm and approaches a low, constant rate as the soil becomes saturated. The permeability of the subsoil becomes the ultimate limiting factor.

Soil type, moisture content, organic matter, vegetative cover, and other factors affect infiltration, but a decrease in rate with time is generally observed. This is shown in Fig. 36, where infiltration rate is plotted against time for two typical soil types. The difference between plots for dry (initial) conditions and wet condition demonstrates the large influence of existing moisture content of the soil.

For purposes of calculation, it is assumed that the soil of the burial site is similar to Houston black loam in its infiltration capacity. The scenario for the maximum volume of water would be to commence with dry soil. This allows a high rate of infiltration at the very start, but within 30 minutes this has fallen by approximately an order of magnitude with additional significant rate decrease in the subsequent hour. It is estimated that during the first three hours of rainfall of intensity sufficient to keep the soil surface covered, the total infiltration will be one inch. After three hours the rate for any continuing rainfall period is 0.05 in/hr, (0.125 cm/hr), the equilibrium flow rate.

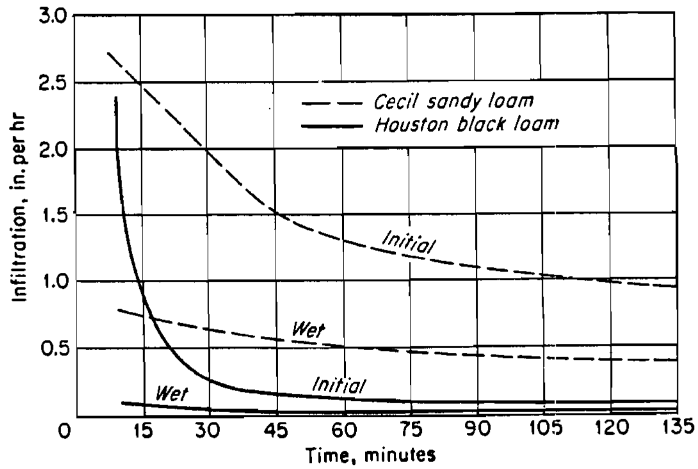


Figure 36 Comparative infiltration rates during initial and wet runs (after Ref. 25)

The total inflow of water into the burial site during a given episode, therefore, depends on the length of time that the surface fo the ground is wet enough to supply 0.05 in. of water per hour. No records of periods of continuous rainfall in the southeast have been located, and the Atlanta Weather Bureau is of the opinion that no such records have been kept. In reviewing the rainfall records for the Atlanta area, it was found that maxima are tabulated for one, two, and seven-day periods. It is considered unlikely that rain would occur continuously for more than a few days, based on seven-day records of 9 inches (10 year return), 10 inches (25 year return) and 12 inches (100 year return). It is therefore concluded that the maximum quantity of rainfall will be 9.25 inches, (~23cm) obtained from the sum of one inch in three hours plus 0.05 in/hr. for 165 additional hours. It is further noted that the return period for this maximum is greater than 10 years, and is more likely to exceed 25 years.

This is based on the assumption of a week during which the rain falls steadily and virtually no surface run-off occurs, a set of circumstances that clearly would not occur very often. The quantity of infiltrated water would also be reduced by evapotranspiration, estimated at 0.25 inch per day. On this basis, the total quantity of water to be considered is reduced to 7.5 inches (18.75cm).

The passage of water from the surface of the ground to the junction with the water table is envisioned as follows: After penetration of the air-ground interface, water proceeds downward at a slow rate determined by the characteristics of the compacted fill soil. It then enters the zone where waste materials have been placed. It is highly unlikely that the waste containers could ever be placed in a very tight configuration and cracks, crevices, and void spaces would be plentiful. Also, any back-filled soil that works into the main volume of waste is not likely to be very well compacted, so the entire waste zone will be conducive to the rapid percolation of water.

The rate of movement of water into the underlying and surrounding undisturbed soil will be lower than the rate of movement through the waste, so a storage volume beneath the waste will be required to prevent water from standing in the waste zone. It is estimated that infiltration will proceed twice as fast through the backfill as through the undisturbed lower strata, so for a steady input of 7.5 inches of water in a week, an accumulation of 2.25 inches (5.6cm) of water can be calculated.

The storage volume under the waste can best be provided by a layer of a highly porous nature. A granular material such as small gravel or coarse sand would be appropriate, but the interstices must be small enough to prevent significant invasion of fines with subsequent clogging. AASHTO number 89 stone would be an appropriate choice, as it would provide a very permeable zone and would not require the placement of a number of layers of different sized media. If compacted to a reasonable density, the void volume of 89 stone is in the 20-25% range. It would therefore require a theoretical depth of 11.25 inches to hold 2.25 inches of water. Such precision is not warranted and specification of one foot (30cm) of this material will assure a very conservative volume.

Placement of a foot of small gravel such as 89 stone under the disposal trenches is a reasonable measure which should provide long-term assurance that the layer would retain its capacity even with a limited amount of siltation from the lower reaches of the backfill.

It may occur that site considerations will make it desirable to increase the size of the drainage area or to move it completely from under the burial area. This can be accomplished by drain lines leading from the layer of emplaced gravel to another drain field. Clay pipes are satisfactory for this type of service as they are resistant to chemical deterioration, can be installed without any particular difficulty, and should remain trouble-free for a very long period of time. They are susceptible to breakage, however, and could be destroyed by the heavy equipment used to place and compact the waste materials.

While the installation of drain lines entirely across the bottom of the excavation within the gravel layer would provide very rapid discharge from the gravel, this is not mandatory. If the lines extend into the gravel a limited distance, the desired result will be obtained because of the very high rate of tranmission of water by the gravel layer. From the practical view, it could be advisable to delay installation of the drain tile and its limited adjacent gravel area until the balance of the trench was already filled and compacted.

More than one line should be installed so that the system could operate in a fairly normal manner, even if some of the pipes were broken or became clogged with silt or roots. In the areas where exfiltration is intended, the pipes would be laid with open joints in ditches with a layer of gravel. Tight pipe joints would be used in any zone where dispersion of the water was not wanted.

The area of the extended drain field will be governed by the relative permeability of the subsoil in relation to the permeability of the soil cap covering the waste. In the situation of a remote drain field of the same area as that of the burial excavation, if the soil permeability is less than half of that of the cap, the potential maximum accumulation of water will be more than the 2.25 inches calculated above. This increase can be offset by a deeper gravel layer or a larger drain field, but the volume of the drain lines themselves may be large enough to be significant. In any event, the effect of pipe volume should be considered.

A downward slope of the drain lines is needed, but it does not have to be a very large slope. The usual design of a drain field involves parallel pipe lines fed by a header, but the long-term reliability of the system can be increased by the addition of extra connections at intervals between the parallel lines. This will provide a grid so that in the event of a stoppage, flow to most points can be provided from the other direction.

No unusual requirements are placed on the subsequent seepage path to the aquifer. A fairly clayey soil and a reasonable distance to the water table are desirable and the orientation of the drain field can be chosen to optimize the final water flow direction in this respect. Since the source term is expected to be lower, the retention capacity of the seepage path also need not be as high as for the saturated flow condition and a wider area can be drawn into service, subject mainly to cost and land use limitations.

CONCLUSIONS

The drained trench approach has been, incorrectly, described as a "controlled release" procedure, which would not be in accordance with 10CFR61 regulations. It would be more appropriate to say that it is a more realistic evaluation of what happens in a burial trench and is a preferable approach to a setting that invites bathtub conditions that would lead to uncontrolled release and a very rapid return of contaminants to the biosphere. The drained trench approach is expected to reduce waste leaching significantly, though additional work is required to determine just how much. By eliminating standing water in the trench, frost and subsidence effects should be reduced. The backfill material would normally be more permeable than the undisturbed soil, resulting in lower residual moisture levels, but in some locations it may be desirable to mix some sand or sandy loam into the backfill.

The extra cost of providing a foot-deep layer of gravel or 89 stone is not significantly higher than the base preparation currently practiced in preparing disposal trenches. The more extensive drain field would entail additional costs compared with current procedures; on the other hand, much of this added cost would be recovered by the lesser need for very rigid and elaborate cap designs that are proposed by some at present (26).

The work has shown the importance of taking unsaturated flow conditions into account in designing a facility and assessing its impact. Although it is easier and "conservative" to model saturated flow, it is evident that the calculated impacts may be orders of magnitude too high and give an unrealistic impression of the radiological consequences of trench construction (27). It is still important to bury predominantly solid waste, but in a careful chosen medium, proper drainage would be expected to provide better insurance in the long run against excessive leaching and release, than reliance on trench cap performance.

ACKNOWLEDGMENTS

We are endebted to Mr. Ed Johnson of the Georgia Highway Department for providing some gravel for this project and to Mr. Jerry A.Connor of the Georgia Tech Physical Plant Department for arranging the trench excavation and supplying sand and other materials.

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APPENDIX A

Water Characteristics, Hydraulic Conductivity and Sorption Models

by F. N. Carneiro de Sousa

What makes the unsaturated flow equation difficult to solve is the fact that the pressure head and the hydraulic conductivity are both a function of the water content; these relations can be incorporated in the model in table form or by means of analytical expressions. In this study the available data for each soil type was fitted to three different analytical relations, which were called Brooks and Corey, Haverkamp, and Van Genuchten models.

The solution of the transport equation needs also a relation to represent the sorption process. The model was developed in such a way that any equilibrium sorption model can be used, and the three most used ones are described in this section. Some alterations have to be done if a kinetic sorption model is to be used.

1. - Water characteristics and Hydraulic Conductivity Models

a - Brooks and Corey

Brooks and Corey (1964) suggested the following relation to represent the soil-water characteristics

$$\frac{\theta - \theta_r}{n - \theta_r} = \left(\frac{\psi_e}{\psi}\right)^{\lambda} \quad \text{(A.1)}$$

where θ is the volumetric water content, n is the porosity, θ_r is the residual water content, ψ is the soil suction, ψ_e is the air-entry value, and λ is the pore-size distribution index.

The associated hydraulic conductivity is given by

$$K = K_s \left(\frac{\theta - \theta_r}{n - \theta_r}\right)^{\frac{2 + 3\lambda}{\lambda}} \quad \text{(A.2)}$$

where K is the unsaturated hydraulic conductivity and K_s is the saturated one. This equation was obtained by Brooks and Corey with the use of the Burdine theory (see Van Genuchten model). If the Mualem theory is used the equation becomes

$$K = K_s \left(\frac{\theta - \theta_r}{n - \theta_r}\right)^{\frac{4 + 5\lambda}{\lambda}} \quad \text{(A.3)}$$

This set of equations is one of the most used to describe the hydraulic properties of the soil.

b - Haverkamp

Haverkamp (Haverkamp et al., 1977) proposed the following relation for the soil-water characteristics based on laboratory infiltration experiments:

$$\theta = \frac{\alpha (n - \theta_r)}{\alpha + |h|^\beta} + \theta_r \qquad (A.4)$$

where n is the porosity, θ_r is the residual water content, h is the pressure head, and α and β are empirical constants.

As is discussed by McKeon (McKeon et al., 1983), this relation provides for the proper behavior of the soil-water characteristics, since as h approaches zero, the water content approaches saturation, and as h assumes large negative values, the water content approaches the residual value.

The associated hydraulic conductivity relation is given by

$$K = K_s \left(\frac{A}{A + |h|^\beta} \right) \qquad (A.5)$$

where K_s is the saturated hydraulic conductivity and A and β are empirical constants.

c - Van Genuchten

Van Genuchten (1978) presents a relation for the soil-water characteristics which is a development of the Haverkamp relation; it is given by

$$\theta = (n - \theta_r)\left(\frac{1}{1 + |\alpha h|^{\beta}}\right)^{\lambda} + \theta_r \tag{A.6}$$

where α and β are empirical constants and $\lambda = 1 - 1/\beta$. This equation provides the same limits and smoothness as those obtained with the Haverkamp model.

The hydraulic conductivity/water content relation presented by Van Genuchten (1980) is an integral form of the Childs and Collis-George (1950) equation, which is an attempt to calculate the unsaturated hydraulic conductivity using a pore-size distribution obtained from the soil-water characteristics curve. Several investigators modified the equation, and Mualem (1976) presented a simple analytical model given by

$$K_r(\theta) = \frac{\left\{ S_e^{\beta} \sum_{i=1}^{m} \frac{2(m-i)+1}{\psi_i^2} \right\}}{\left\{ \sum_{i=1}^{m} \frac{2(m-i)+1}{\psi_i^2} \right\}} \tag{A.7}$$

where m represents the total number of intervals into which the water content is divided (water characteristics curve), n is the number of intervals up to a prescribed value of θ, β is a constant related to the pore-size distribution, $S_e = (\theta - \theta_r) / (n - \theta_r)$, and $K_r = K/K_s$. If β =0, Collis-George equation is obtained; if β = 4/3, it becomes Millington and Quirk (1959) equation; if β = 1 Kunze (Kunze et al., 1968) is obtained. Mualem (1976) presented an alternative formulation given by

$$K_r = (S_e)^{1/2} \left[\int_0^{S_e} \frac{dS_e}{dh} \Big/ \int_0^1 \frac{dS_e}{dh} \right]^2 \tag{A.8}$$

A similar equation is given by Burdine (1958)

$$K_r = S_e^2 \left[\int_0^{S_e} \frac{1}{h^2}\,dx \Big/ \int_0^1 \frac{1}{h^2}\,dx \right] \tag{A.9}$$

The equation presented by Van Genuchten (1980) is an integral form of the Millington and Quirk equation, and is given by

$$K = K_s\, S_e^{1/2} \left[1 - \left(1 - S_e^{1/\lambda} \right)^{\lambda} \right]^2 \tag{A.10}$$

where $S_e = (\theta - \theta_r)/(n - \theta_r)$, and λ and β and α (from eq. A. 6) are empirical constants obtained from the shape of the water characteristics curve. The advantage of this model is the ability to fit data in the near saturation range.

2-Equilibrium Sorption Isotherms

a-Linear Adsorption

The linear adsorption isotherm is the most common relation used to simulate the sorption of radionuclides by the soil particles. It is given by

$$S = K_d C \tag{A.11}$$

where S is the amount of solution absorbed by the soil matrix, C is the concentration of solute in the soil solution and K_d is the distribution coefficient. The velocity of the tracer (V_t) is related to the water volocity (V_e) by

$$V_t = V_w/R \tag{A.12}$$

where R is the retardation factor which is given by

$$R=1 + \frac{\rho K_d}{\theta} \tag{A.13}$$

where ρ is the bulk density.

The disadvantage of this relation is that it assumes equilibrium conditions, and it does not describe a maximum quantity of adsorption. On the other hand, its use makes the transport equation linear, facilitating the numerical simulation. A similar relation is presented by Lapidus and Amundson (1952),

$$S = K_1 C + K_2 \tag{A.14}$$

where K_1 and K_2 are constants.

<u>b - Freundlich Isotherm</u>

The Freundlich (1926) isotherm is given by

$$S=K C^n \tag{A.15}$$

where S is the amount of solute adsorbed per unit weight of soil, C is the equilibrium solute solution concentration, and K and n are constants. If n is equal to zero, it becomes the linear isotherm. The disadvantages are that equilibrium conditions are assumed, it does not specify a maximum quantity of adsorption, and its use makes the transport equation non-linear, which implies in an iterative solution.

c-Langmuir Isotherm

The Langmuir isotherm (1918) was originally developed to describe the adsorption of gas molecules onto the surface of solids; it was after extended to represent the adsorption of aqueous solutes onto solid sorbates. It is given by

$$S = \frac{K\ b\ C}{1+KC} \qquad (A.16)$$

where S is the amount of solute adsorbed for unit mass of solid, C is the equilibrium solute concentration, K is a constant related to the energy of adsorption, and b is the maximum amount which can be adsorbed by the solid. It becomes the linear isotherm as C approaches zero. The disadvantage is that it assumes equilibrium conditions, and the transport equation becomes non-linear when it is used.

Other equilibrium sorption isotherms as well as kinetic sorption models are given by Travier and Etnier (1981).

APPENDIX B

MODEL IMPLEMENTATION

In this appendix a description is given of the one-dimensional unsaturated flow and transport mode. The program consists of a main program and 12 subroutines. The main program is responsible for the organization of the program, basically, it performs the scheme shown in Fig. B.1.

Subroutine INPU1 is used to initialize the values of all variables needed for the solution of the water flow equation; it defines the geometry and the initial and boundary conditions of the case under study; it also introduces the physical and chemical properties of the soils. Subroutine INPU2 is used to introduce the values of the variables needed to obtain the solution of the transport equation; it includes the initial and boundary conditions as well as the soil properties that were not already introduced by INPU1.

Subroutine SET performs a coordinate transformation; it changes the global coordinates of the nodes of each element to a local coordinate system, which simplifies the evaluation of the element matrices.

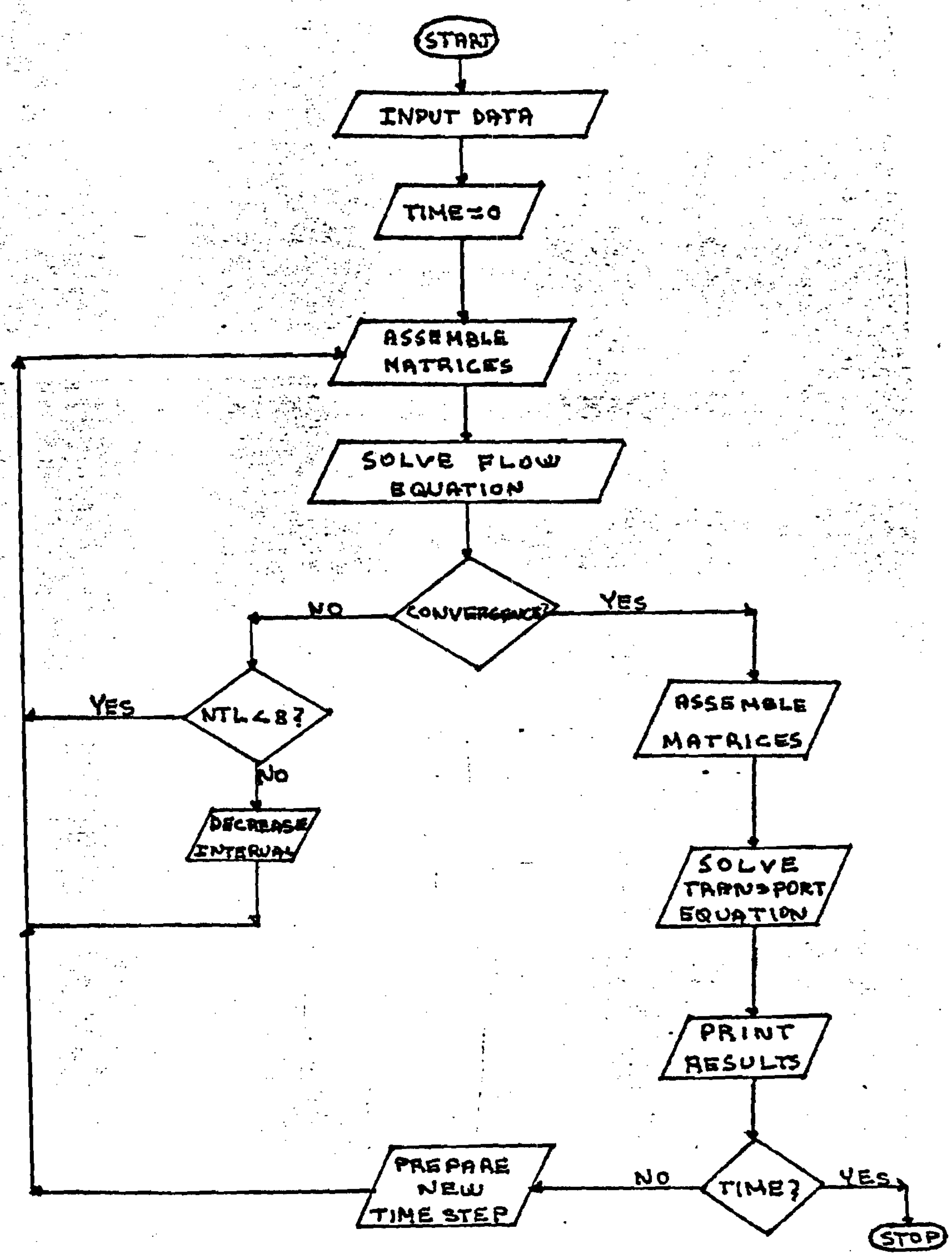

Figure B-1 Model Flow Diagram

Subroutine ELEM generates the local element matrices by calculating each coefficient of the matrices necessary to solve the matrix flow equation. Subroutine ELEM 1 does the same calculations for the transport equation. The soil properties needed for the evaluation of the matrix coefficients are calculated in subroutine HCWC, which is called by subroutine ELEM.

Once the global matrices are assembled, a set of partial differential equations is obtained; these equations are solved by applying a finite difference scheme, and this is done in subroutine CALC1. This subroutine is also responsible for the introduction of the boundary conditions. The output of this subroutine is a system of ordinary equations which is solved by subroutine SOLVE. The method used to solve these equations is the Thomas algorithm, which is a special form of the Gaussian elimination method.

When the solution is obtained for the flow equation, the convergence criteria is checked by subroutine ERROR. If convergence is not attained, the iterative process continues; if convergence is attained, the variables needed for the solution of the transport equation are evaluated by subroutine PROP and the transport equation is then solved. Subroutine OUT presents the values of the hydraulic head, water content, and solute concentration at each time interval.

Table B.1 presents the major variables used in the numerical implementation of the program; Table B2 presents the input cards needed to solve the flow equation, and Table B.3 presents the listing of the actual program.

TABLE B.1 - PROGRAM VARIABLES

AG(30.3)	- Global matrix
AI(3)	- Residual Water Content of each soil
AL1	- Distance between the two last nodes of the soil column.
ALF(3)	- Compressibility of the soil
BI(3)	- Value of α in eq. A.4 and A.5, and value of ψ_a in eq. A.1
BUD(3)	- Bulk density of the soils.
CI(3)	- Pore-size distribution index.
CL	- Value of the constant concentration at the last node of the column when a constant boundary condition is used.
CO(20)	- Variable concentration at the top of the column when a variable boundary condition is used.
CON(30)	- Concentration at time $t+\Delta t$.
CONI(30)	- Initial concentration profile.
COO	- Constant concentration at surface when a constant boundary condition is used.
DEV(30)	- Value of $\partial h/\partial t$ at each node.
DEVO(30)	- Value of $\partial \theta/\partial t$ at each node.
DI(3)	- Value of A in EQ. A.5
DICO(30)	- Distribution coefficient of each soil
DIFU(3)	- Diffusion coefficient of each soil
DISP(3)	- Dispersivity of each soil.
EI(3)	- Value of β in eq. A.5
ERR1	- Value of ε_1 in eq. VII. 31.
ERR2	- Value of ε_2 in eq. VII.31.
FLUX(30)	- Value of the water flux at each node.
GAM(3)	- Zero-order rate constant of each soil.

HC1 - Hydraulic conductivity of the first node

HCL - Hydraulic conductivity of the last node.

HCOS(3) - Saturated hydraulic conductivity of each soil.

HEDI1 - Value of the pressure head at first node of each element at time

HEDI2 - Value of the pressure head at second node of each element at time

HEDIL(30) - Value of the pressure head at each node at time t.

HEDIN(30) - Value of the pressure head at each node at time $t+\frac{1}{2}\Delta t$.

HEDIX(30) - Value of the pressure head at each node at time $t+\Delta t$.

HEDO - Value of the initial pressure head if it is constant through the soil column.

HL - constant pressure head at the last node if a constant boundary condition is used.

HO - Constant pressure head at surface if a constant boundary condition is used.

I1 - Determines which sorption model is used. .
= 1 Linear adsorption isotherm.

I2 - Determines which soil-water characteristics model is used.

= 1 Brooks and Corey
= 2 Van Genuchten
= 3 Haverkamp

I3 - Determines which hydraulic conductivity model is used.
= 1 Brooks and Corey
= 2 Van Genuchten
= 3 Haverkamp

I4 - If it is equal to one QO (I) = constant.

ICON(30,2)- Relates each node number to its element.

IE - Constant used to indicate if convergence is attained.

IK - Constant used to indicate which soil type applies to each element.

IKK - Constant used to indicate which value of the constant flux at surface is being used

TABLE B.1 cont.

ISA	- Constant used to indicate if the initial concentration is constant over the whole soil profile.
ISP	= 1 equally spaced nodes.
ISS	= 1 Constant initial pressure head.
IST	= 1 Homogeneous soil
ISU	= 1 Transport model is used
ISX	= 1 Mass lumping is used.
JI(3)	- Contains the node number at which each soil type ends.
K1	= 1 Constant concentration at surface.
K2	= 1 Constant flux of concentration at surface at each specified time.
K3	= 1 Free draining profile.
K4	= 1 Constant concentration at last node.
K21	= 1 Constant flux of concentration at surface.
KB1	= 1 Constant flux at surface.
KB2	= 1 Constant flux at last node.
KB3	= 1 Constant pressure head at surface.
KB4	= 1 Constant pressure head at last node.
KB5	= 1 Variable flux at last node.
NELEM	- Number of elements used.
NEWN(2)	- Contains the nodes numbers for each element.
NL	- Number of iterations at each time step.
NNODE	- Number of nodes.
NST	- Maximum number of iterations allowed at each time step.
NT	- Counts number of time steps.
NTM	- Maximum number of time steps allowed.

TABLE B.1 cont.

PF(30)	- Global matrix.
PORO(3)	- Porosity of each soil type.
QL	- Constant flux at last node.
QO(20)	- Values of constant flux at different times at surface.
SCAP1	- Soil water capacity of first node of an element.
SCAP2	- Soil water capacity at second node of an element.
SS(3)	- Specific storage of each soil.
TETIX(30)	- Water content at each node at time .
TETOX(30)	- Water content at each node at time t.
TI	- Time since start of simulation.
TIM	- Value of the time interval at time t.
TIMAX	- Maximum time interval allowed.
TIME	- Total time of simulation.
TIMEX(20)	- Time at which constant flux ends at the surface.
TIMIN	- Minimum time interval allowed.
TIVAL	- Time interval at time t+ t
TORT(3)	- Tortuosity factor of each soil.
XL	- Length of the soil profile.
XLAM	- Decay rate fo the radionuclide under study.
XMG(30,3)	- Global matrix.
W	= 0 explicit algorithm is used. = 1/2 Crank-Nicholson algorithm is used. = 1 Implicit algorithm is used.
Z(30)	- global coordinates of the nodes.

TABLE B.2 - INPUT DATA FOR FLOW EQUATION

CARDS	COLUMNS	FORMAT	VARIABLE
1	1-8	F8.3	XL
	9-16	F8.3	TIME
	17-24	F8.5	TTIVAL
	25-32	F8.3	TIMAX
	33-40	F8.5	TIMIN
	41-48	F8.3	
	49-53	I5	NELEM
	54-58	I5	NTM
	59-63	I5	NST
2	1	I5	ISP
3	1	I5	ISS
4	1	F8.3	HEDO
5	1	I5	IST
6-8	1-8	F8.3	AI(3)
	9-16	F8.3	BI(3)
	17-24	F8.3	CI(3)
	25-32	F8.3	DI(3)
	33-40	F8.3	DI(3)
	41-48	F8.3	HCOS(3)
	49-56	F8.3	PORO(3)
	57-64	E8.3	SS(3)
	65-69	I5	JI(3)
9	1-5	I5	ISU
	6-13	F8.3	ERR1
	14-21	F8.3	ERR2
	22-26	I5	I1
	27-31	I5	I2
	32-36	I5	I3
	36-40	I5	I4
10	1-5	I5	KB1
	6-10	I5	KB2
	11-18	F8.3	QL
	19-23	I5	KB3
	24-28	I5	KB4
	29-35	F8.3	HO
	36-42	F8.3	HL
	43-47	I5	KB5
11	1	F8.3	QOO
12	1	I5	ISX

TABLE B.3 - PROGRAM LISTING

```
      PROGRAM ODIT(IN,OUT,TAPE5=IN,TAPE6=OUT)
      DIMENSION Z(30),ICON(30,2),HEDIN(30),AI(3),BI(3),CI(3),DI(3),
     1EI(3),HCOS(3),PORO(3),SS(3),TIMEX(20),QO(20),XSG(30,3),
     2XMG(30,3),XPG(30),ZE(2),NEWN(2),JI(3),XM(2,2),XS(2,2),
     3XP(2),TMG(30,3),FPG(30,3),HEDIX(30),HEDIL(30),PF(30),
     4TETIX(30),HEDIS(30),HEDIP(30)
*     ----READ INPUT VALUES----
      REWIND 6
      CALL INPU1(XL,TIME,TIVAL,TIMAX,TIMIN,NELEM,W,NNODE,Z,HEDIN,
     1AI,BI,CI,DI,EI,HCOS,PORO,SS,ISU,I1,I2,I3,ERR1,ERR2,KB1,KB2,
     2KB3,KB4,KB5,QO,QL,HO,HL,ISX,TIMEX,NTM,NST,JI,ICON)
*     ----DETERMINE IF TRANSPORT EQUATION IS USED----
*     IF(ISU.LT.1)GO TO 2
*     CALL INPU2(
*   2 CONTINUE
      NL=1
      NT=1
      NNN=1
      DO 3 I=1,NNODE
       HEDIP(I)=HEDIN(I)
       HEDIS(I)=HEDIN(I)
    3 HEDIL(I)=HEDIN(I)
      TIM=TIVAL
      IKK=1
      IK=1
      TI=0
      TI=TI+TIVAL
    6 DO 10 I=1,NNODE
      DO 10 J=1,3
      XSG(I,J)=0
      XMG(I,J)=0
   10 XPG(I)=0
*     ----DETERMINE LOCAL MATRICES----
      DO 20 I=1,NELEM
      HEDI1=HEDIN(I)
      HEDI2=HEDIN(I+1)
      DO 15 J=1,2
   15 NEWN(J)=ICON(I,J)
*      WRITE(6,1102)NEWN
*1102 FORMAT(/2I5,'NEW NODE')
      CALL SET(NEWN,ZE,Z,NELEM,ISP,XL)
      CALL ELEM(HEDI1,HEDI2,PORO,SS,ISX,I2,I3,HCOS,AI,BI,CI,DI,EI,
     1JI,NEWN,IK,ZE,XM,XS,XP,NNODE,HC1,HCL,AL1)
*     ----ASSEMBLE GLOBAL MATRICES----
   20 CALL ASSEM(NEWN,XM,XMG,XS,XSG,XP,XPG)
*     ----INTRODUCE BOUNDARY CONDITIONS----
      CALL CALC1(TIVAL,HEDIS,XMG,XSG,XPG,NNODE,W,KB1,KB2,KB3,KB4,
     1KB5,QO,QL,HO,HL,TIMEX,TI,HC1,HCL,AL1,IKK,TMG)
      CALL SOLVE(TMG,XPG,HEDIX,FPG,NNODE)
*     ----CHECK FOR CONVERGENCE----
      CALL ERROR(HEDIX,HEDIL,IE,ERR1,ERR2,NNODE)
*     WRITE(6,111)(HEDIX(I),HEDIL(I),I=1,NNODE)
* 111 FORMAT(3X,F8.3,3X,F8.3)
      IF(NNN.GT.1)GO TO 21
      TI=TIVAL
   21 IF(IE.EQ.0)GO TO 50
      IF(NL.LE.NST)GO TO 25
      TI=TI-.5*TIVAL
      TIVAL=0.5*TIVAL
      IF(TIVAL.LT.TIMIN)GO TO 100
      DO 22 I=1,NNODE
       HEDIN(I)=HEDIS(I)+(TIVAL/(2*TIM))*(HEDIS(I)-HEDIP(I))
```

```
22    HEDIL(I)=HEDIN(I)
      NL=1
      GO TO 6
25    DO 30 I=1,NNODE
     HEDIN(I)=0.5*(HEDIX(I)+HEDIS(I))
30    HEDIL(I)=HEDIX(I)
      NL=NL+1
      GO TO 6
*     ----CONVERGENCE IS ATTAINED----
50     IF(NNN.GT.1)GO TO 55
       TI=TIVAL
55    DO 57 I=1,NNODE
      H=ABS(HEDIX(I))
      HH=29.484
      IF(H.GT.HH)GO TO 56
      TETIX(I)=.4531-.02732*LOG(H)
      GO TO 57
56    TETIX(I)=.6829-.09524*LOG(H)
57    CONTINUE
      CALL OUT(TI,Z,HEDIX,NT,NL,NNODE,TETIX)
       NNN=NNN+1
      DO 60 I=1,NNODE
      HEDIN(I)=HEDIX(I)+(TIVAL/(2*TIM))*(HEDIX(I)-HEDIS(I))
      HEDIP(I)=HEDIS(I)
      HEDIS(I)=HEDIX(I)
60    HEDIL(I)=HEDIN(I)
      IF(NL.GT.3)GO TO 70
      TIVAL=1.5*TIVAL
      IF(TIVAL.LE.TIMAX)GO TO 70
      TIVAL=TIMAX
70    NT=NT+1
      TI=TI+TIVAL
      IF(TI.GT.TIME)GO TO 100
      IF(NT.GT.NTM)GO TO 100
      NL=1
      TIM=TIVAL
      GO TO 6
100   WRITE(6,1001)TI,NT
1001  FORMAT(3X,"PROGRAM TERMINATED WITH TI=",1X,F8.5,2X,"AND NT=",
     1 2X,I5)
      STOP
      END
      SUBROUTINE INPU1(XL,TIME,TIVAL,TIMAX,TIMIN,NELEM,W,NNODE,Z,
     1 HEDIN,AI,BI,CI,DI,EI,HCOS,PORO,SS,ISU,I1,I2,I3,ERR1,ERR2,
     2 KB1,KB2,KB3,KB4,KB5,Q0,QL,H0,HL,ISX,TIMEX,NTM,NST,JI,ICON)
      DIMENSION Z(30),HCOS(3),PORO(3),SS(3),TIMEX(20),Q0(20),JI(3),
     1 ICON(30,2),HEDIN(30),AI(3),BI(3),CI(3),DI(3),EI(3)
      WRITE(6,1000)
      READ(5,1010)XL,TIME,TIVAL,TIMAX,TIMIN,W,NELEM,NTM,NST
      WRITE(6,1020)XL,TIME,TIVAL,TIMAX,TIMIN,W,NELEM,NTM,NST
      NNODE=NELEM+1
*     ----DETERMINE GLOBAL COORDINATES OF THE NODES----
      READ(5,1030)ISP
      DO 1 I=1,NNODE
1     Z(I)=0
      IF(ISP.LT.1)GO TO 5
      DO 2 I=1,NNODE
      Z(I)=(I-1)*XL/NELEM
2     WRITE(6,1040)I,Z(I)
      GO TO 10
5     DO 7 I=1,NNODE
      READ(5,1050)Z(I)
7     WRITE(6,1040)I,Z(I)
```

```
      DO 12 J=1,2
12    ICON(I,J)=I+J-1
*     ----OBTAIN INITIAL PRESSURE HEADS----
      READ(5,1030)ISS
      IF(ISS.LT.1)GO TO 17
      READ(5,1050)HEDO
      WRITE(6,1070)HEDO
*     DO 15 I=1,NNODE
      DO 15 I=1,12
      XX=.15+.000833*(I-1)*5/1
      XXX=(.6829-XX)/.09524
      HEDIN(I)=-EXP(XXX)
15    WRITE(6,1040)I,HEDIN(I)
      DO 16 I=13,26
      HEDIN(I)=HEDO
16    WRITE(6,1040)I,HEDIN(I)
* 15  HEDIN(I)=HEDO
      GO TO 20
17    DO 18 I=1,NNODE
      READ(5,1050)HEDIN(I)
18    WRITE(6,1040)I,HEDIN(I)
20    READ(5,1030)IST
      IF(IST.LT.1)GO TO 25
      READ(5,1090)AII,BII,CII,DII,EII,HCOSI,POROI,SSI,JII
      WRITE(6,1100)AII,BII,CII,DII,EII,HCOSI,POROI,SSI,JII
      DO 22 I=1,3
      AI(I)=AII
      BI(I)=BII
      CI(I)=CII
      DI(I)=DII
      EI(I)=EII
      HCOS(I)=HCOSI
      PORO(I)=POROI
      JI(I)=JII
22    SS(I)=SSI
      GO TO 30
25    DO 28 I=1,3
      READ(5,1090)AI(I),BI(I),CI(I),DI(I),EI(I),HCOS(I),PORO(I),
     1 SS(I),JI(I)
28    WRITE(6,1100)AI(I),BI(I),CI(I),DI(I),EI(I),HCOS(I),PORO(I),
     1 SS(I),JI(I)
30    CONTINUE
*     ----DETERMINE IF TRANSPORT MODEL IS USED----
      READ(5,1105)ISU,ERR1,ERR2,I1,I2,I3,I4
*     ----OBTAIN BOUNDARY CONDITIONS----
      READ(5,1110)KB1,KB2,QL,KB3,KB4,HO,HL,KB5
      IF(KB3.LT.1)GO TO 31
      HEDIN(1)=HO
31    IF(KB4.LT.1)GO TO 315
      HEDIN(NNODE)=HL
*     HEDIN(NNODE)=HL
*     IF(I4.LT.1)GO TO 32
315   READ(5,1050)QQQ
      DO 316 I=1,20
      TIMEX(I)=TIME
316   QQ(I)=0.
      QQ(1)=0.
      TIMEX(1)=TIME/2.
      QQ(2)=QQQ
      TIMEX(2)=TIME
      GO TO 40
32    DO 35 I=1,20
```

```
      READ(5,1120)TIMEX(I),QO(I)
 35   WRITE(6,1130)TIMEX(I),QO(I)
*     ----DETERMINE IF MASS LUMPING IS USED----
 40   READ(5,1030)ISX
*     ----
1000  FORMAT(//,7X,"UNSATURATED FLOW AND TRANSPORT",/)
1010  FORMAT(2F8.3,F8.5,F8.3,F8.5,F8.3,3I5)
1020  FORMAT(3X,"XL=",F8.3,3X,"TIME=",F8.3,3X,"TIVAL=",E8.3,3X,
     1"TIMAX=",F8.3,/,3X,"TIMIN=",E8.3,3X,"W=",F8.3,3X,"NELEM=",
     2I5,3X,"NTM=",I5,3X,"NST=",I5)
1030  FORMAT(I5)
1040  FORMAT(4X,I4,6X,F8.3)
1050  FORMAT(F8.3)
1070  FORMAT(/,4X,"HEDO=",F8.3)
1090  FORMAT(7F8.3,E8.3,I5)

1100  FORMAT(3X,7(3X,F8.3),3X,E8.3,3X,I5)
1105  FORMAT(I5,2F8.3,4I5)
1110  FORMAT(2I5,F8.3,2I5,2F8.3,I5)
1120  FORMAT(2F8.3)
1130  FORMAT(3X,F8.3,3X,F8.3)
      RETURN
      END
      SUBROUTINE SET(NEWN,ZE,Z,NELEM,ISP,XL)
      DIMENSION Z(30),ZE(2),NEWN(2)
      IF(ISP.LT.1)GO TO 1
      ZE(1)=0
      ZE(2)=XL/NELEM
      GO TO 5
 1    J=NEWN(1)
      JJ=NEWN(2)
      ZE(1)=0
      ZE(2)=Z(JJ)-Z(J)
 5    RETURN
      END
      SUBROUTINE ELEM(HEDI1,HEDI2,PORO,SS,ISX,I2,I3,HCOS,AI,BI,
     1CI,DI,EI,JI,NEWN,IK,ZE,XM,XS,XP,NNODE,HC1,HCL,AL1)
      DIMENSION PORO(3),SS(3),HCOS(3),AI(3),BI(3),CI(3),DI(3),
     1EI(3),JI(3),NEWN(2),ZE(2),XM(2,2),XS(2,2),XP(2)
      IAS=NEWN(1)
      IASS=JI(IK)
      IF(IAS.LT.IASS)GO TO 5
      IK=IK+1
 5    AL=ZE(2)-ZE(1)
      CALL HCWC(HCO1,HCO2,TETI1,TETI2,SCAP1,SCAP2,HEDI1,HEDI2,
     1I2,I3,IK,PORO,HCOS,AI,BI,CI,DI,EI,IAS)
      IF(ISX.EQ.1)GO TO 10
      XM(1,1)=(AL/12)*(3*(TETI1*SS(IK)/PORO(IK)+SCAP1)+(TETI2*SS(IK)
     1/PORO(IK)+SCAP2))
      XM(1,2)=(AL/12)*(TETI1*SS(IK)/PORO(IK)+SCAP1+TETI2*SS(IK)/
     1PORO(IK)+SCAP2)
      XM(2,1)=XM(1,2)
      XM(2,2)=(AL/12)*(3*(TETI2*SS(IK)/PORO(IK)+SCAP2)+(TETI1*SS(IK)
     1/PORO(IK)+SCAP1))
      GO TO 15
 10   XM(1,1)=(AL/6)*(2*(TETI1*SS(IK)/PORO(IK)+SCAP1)+(TETI2*SS(IK)
     1/PORO(IK)+SCAP2))
      XM(1,2)=0
      XM(2,1)=0
      XM(2,2)=(AL/6)*(2*(TETI2*SS(IK)/PORO(IK)+SCAP2)+(TETI1*SS(IK)
     1/PORO(IK)+SCAP1))
 15   XS(1,1)=(1/(2*AL))*(HCO1+HCO2)
      XS(1,2)=-XS(1,1)
```

```fortran
      XS(2,1)=XS(1,2)
      XS(2,2)=XS(1,1)
      XP(1)=0.5*(HC01-HC02)
      XP(2)=XP(1)
      IF(IAS.GT.1)GO TO 30
      HC1=HC01
* 30  DO 22 I=1,2
*     DO 22 J=1,2
* 22  WRITE(6,112)XM(I,J),XS(I,J),XP(I)
*112  FORMAT(3X,3(E9.3,3X))
*     WRITE(6,111)HC1
*111  FORMAT(/,3X,"HC1 =",F8.3)
  30  IASL=NEWN(2)
      IF(IASL.LT.NNODE)GO TO 40
      AL1=AL
      HCL=HC02
  40  RETURN
      END
      SUBROUTINE HCWC(HC01,HC02,TETI1,TETI2,SCAP1,SCAP2,HEDI1,
     1HEDI2,I2,I3,IK,PORO,HCOS,AI,BI,CI,DI,EI,IAS)
      DIMENSION PORO(3),HCOS(3),AI(3),BI(3),CI(3),DI(3),EI(3)
*    1TETIX(30)
*     ----DETERMINE WHICH WATER CONTENT MODEL APPLIES----
*     ----BROOKS AND COREY MODEL----
      HED11=ABS(HEDI1)
      HED22=ABS(HEDI2)
      IF(I2.GT.1)GO TO 10
      XP=CI(IK)
      TETI1=AI(IK)+((PORO(IK)-AI(IK))*(BI(IK)/HED11)**XP)
      TETI2=AI(IK)+((PORO(IK)-AI(IK))*(BI(IK)/HED22)**XP)
      XPPP=1/XP
      XPP=(XP+1)/XP
      SCAP1=(XP/(BI(IK)*(PORO(IK)-AI(IK))**XPPP*(TETI1-AI(IK))**XPP))
      SCAP2=(XP/(BI(IK)*(PORO(IK)-AI(IK))**XPPP*(TETI2-AI(IK))**XPP))
      GO TO 50
*     ----VAN GENUCHTEN MODEL----
  10  IF(I2.GT.2)GO TO 20
      XP=CI(IK)
      XPP=1-1/XP
      XP1=XP-1
      XPP1=XPP+1
 TETI1=(PORO(IK)-AI(IK))*((1/(1+(BI(IK)*HED11)**XP))**XPP)+AI(IK)
 TETI2=(PORO(IK)-AI(IK))*((1/(1+(BI(IK)*HED11)**XP))**XPP)+AI(IK)
      SCAP1=XPP*(PORO(IK)-AI(IK))*((1/(1+(BI(IK)*HED11)**XP))**XPP1)*
     1XP*(BI(IK)**XP)*(HED11**XP1)
      SCAP2=XPP*(PORO(IK)-AI(IK))*((1/(1+(BI(IK)*HED22)**XP))**XPP1)*
     1XP*(BI(IK)**XP)*(HED22**XP1)
      GO TO 50
      ----HAVERKAMP MODEL----
  20  IF(I2.GT.3)GO TO 30
      XP=CI(IK)
      XPP=XP-1
      TETI1=BI(IK)*(PORO(IK)-AI(IK))/(BI(IK)+HED11**XP)+AI(IK)
      TETI2=BI(IK)*(PORO(IK)-AI(IK))/(BI(IK)+HED22**XP)+AI(IK)
      SCAP1=BI(IK)*XP*(PORO(IK)-AI(IK))*(1/(BI(IK)+HED11**XP)**2)*
     1HED11**XPP
      SCAP2=XP*BI(IK)*(PORO(IK)-AI(IK))*(1/(BI(IK)+HED22**XP)**2)*
     1HED22**XPP
      ----DETERMINE WHICH HYDRAULIC CONDUCTIVITY MODEL APPLIES----
      ----WARRICK MODEL----
  30  IF(I2.GT.4)GO TO 50
      XP=-29.484
      XPP=-14.495
```

```
      IF(HEDI1.GT.XP)GO TO 32
      TETI1=.6829-.09524*LOG(HED11)
      HCO1=1934000/(HED11)**3.4095
      SCAP1=-.09524/HEDI1
      GO TO 34
 32   TETI1=.4531-.02732*LOG(HED11)
      HCO1=516.8/(HED11)**0.97814
      SCAP1=-.02732/HEDI1
 34   IF(HEDI2.GT.XP)GO TO 36
      TETI2=.6829-.09524*LOG(HED22)
      HCO2=1934000/(HED22)**3.4095
      SCAP2=-.09524/HEDI2
      GO TO 100
 36   TETI2=.4531-.02732*LOG(HED22)
      HCO2=516.8/(HED22)**.97814
      SCAP2=-.02732/HEDI2
      GO TO 100
*     ----BROOKS AND COREY MODEL----
 50   IF(I3.GT.1)GO TO 60
      XP=(2+3*CI(IK))/CI(IK)
      HCO1=HCOS(IK)*((TETI1-AI(IK))/(PORO(IK)-AI(IK)))**XP
      HCO2=HCOS(IK)*((TETI2-AI(IK))/(PORO(IK)-AI(IK)))**XP
      GO TO 100
*     ----VAN GENUCHTEN MODEL----
 60   IF(I3.GT.2)GO TO 70
      XP=1-1/CI(IK)
      XPP=1/XP
      HCO1=HCOS(IK)*((TETI1-AI(IK))/(PORO(IK)-AI(IK)))**0.5*(1-(1-((
     1TETI1-AI(IK))/(PORO(IK)-AI(IK)))**XPP)**XP)**2
      HCO2=HCOS(IK)*((TETI2-AI(IK))/(PORO(IK)-AI(IK)))**0.5*(1-(1-((
     1TETI2-AI(IK))/(PORO(IK)-AI(IK)))**XPP)**XP)**2
      GO TO 100
*     ----HAVERKAMP MODEL----
 70   IF(I3.GT.3)GO TO 100
      XP=EI(IK)
      HCO1=HCOS(IK)*(DI(IK)/(DI(IK)+HED11**XP))

      HCO2=HCOS(IK)*(DI(IK)/(DI(IK)+HED22**XP))
 100  IF(HEDI1.LE.0)GO TO 150
      TETI1=PORO(IK)
      SCAP1=0
      HCO1=HCOS(IK)
 150  IF(HEDI2.LE.0)GO TO 200
      TETI2=PORO(IK)
      SCAP2=0
      HCO2=HCOS(IK)
* 200 TETIX(IAS)=TETI1
*     IF(IAS.LT.25)GO TO 300
*     IIAS=IAS+1
*     TETIX(IIAS)=TETI2
* 201 WRITE(6,101)TETI1,TETI2,HCO1,HCO2,SCAP1,SCAP2
*101  FORMAT(3X,6(E9.3,2X))
 200  RETURN
      END
      SUBROUTINE ASSEM(NEWN,XM,XMG,XS,XSG,XP,XPG)
      DIMENSION NEWN(2),XM(2,2),XMG(30,3),XS(2,2),XSG(30,3),
     *XP(2),XPG(30)
      NDN=2
      DO 11 I=1,2
      DO 10 J=1,2
      II=NEWN(I)
      JJ=NEWN(J)
      [illegible] JJ-II
```

```
      XMG(II,KK)=XMG(II,KK)+XM(I,J)
10    XSG(II,KK)=XSG(II,KK)+XS(I,J)
11    XPG(II)=XPG(II)+XP(I)
* 10  WRITE(6,15)(XMG(II,KK),XSG(II,KK),XPG(II),I=1,NNODE)
* 15  FORMAT(3X,3(E8.3,3X))
      RETURN
      END
      SUBROUTINE CALC1(TIVAL,HEDIS,XMG,XSG,XPG,NNODE,W,KB1,KB2,KB3,
     1KB4,KB5,QO,QL,HO,HL,TIMEX,TI,HC1,HCL,AL1,IKK,TMG)
      DIMENSION HEDIS(30),XMG(30,3),XSG(30,3),XPG(30),TMG(30,3),
     1FPG(30,3),TIMEX(20),QO(20)
      DO 1 I=1,NNODE
      DO 1 J=1,3
      TMG(I,J)=0
1     FPG(I,J)=0
*     ----DETERMINE IF NEUMANN VARIABLE FLUX APPLIES----
      IF(KB5.LT.1)GO TO 5
      AAL=HCL/AL1
      GO TO 7
5     AAL=0
7     DO 10 I=1,NNODE
      DO 10 J=1,3
      TMG(I,J)=XMG(I,J)/TIVAL+W*XSG(I,J)
10    FPG(I,J)=XMG(I,J)/TIVAL+(W-1)*XSG(I,J)
      TMG(NNODE,1)=TMG(NNODE,1)-W*AAL
      TMG(NNODE,2)=TMG(NNODE,2)+W*AAL
      FPG(NNODE,1)=FPG(NNODE,1)-(W-1)*AAL
      FPG(NNODE,2)=FPG(NNODE,2)+(W-1)*AAL
      DO 15 I=1,NNODE
      DO 15 J=1,3
15    XMG(I,J)=0
      DO 20 J=2,3
      L=J-1
20    XMG(1,1)=XMG(1,1)+FPG(1,J)*HEDIS(L)
      II=NNODE-1
      DO 25 I=2,II
      DO 25 J=1,3
      K=I+J-2
25    XMG(I,1)=XMG(I,1)+FPG(I,J)*HEDIS(K)
      DO 30 J=1,2
      L=NNODE-2+J
30    XMG(NNODE,1)=XMG(NNODE,1)+FPG(NNODE,J)*HEDIS(L)
*     ----DETERMINE IF CONSTANT FLUX APPLIES----
      TTT=TIMEX(IKK)
      IF(TI.LT.TTT)GO TO 35
      IKK=IKK+1
35    QQ1=QO(IKK)-HC1
      QQ2=HCL-QL
      IF(KB1.EQ.1)GO TO 40
      QO(IKK)=0
40    IF(KB2.EQ.1)GO TO 45
      QL=QO
45    XPG(1)=XPG(1)+XMG(1,1)+QQ1
      L=NNODE-1
      DO 50 I=2,L
50    XPG(I)=XPG(I)+XMG(I,1)
      XPG(NNODE)=XPG(NNODE)+XMG(NNODE,1)+QQ2
*     ----DETERMINE IF CONSTANT HYDRAULIC HEAD APPLIES----
      IF(KB3.LT.1)GO TO 60
      TMG(1,2)=1
      TMG(1,3)=0
      XPG(2)=XPG(2)-HO*TMG(2,1)
      XPG(1)=HO
```

```
      TMG(2,1)=0
60    IF(KB4.LT.1)GO TO 70
      NN=NNODE-1
      XPG(NNODE)=HL
      XPG(NN)=XPG(NN)-HL*TMG(NN,3)
      TMG(NNODE,1)=0
      TMG(NNODE,2)=1
      TMG(NN,3)=0
70    CONTINUE
*     DO 100 I=1,NNODE
*     DO 100 J=1,3
* 100 WRITE(6,110)FPG(I,J),TMG(I,J),XPG(I)
* 110 FORMAT(3X,3(E9.3,3X))
      RETURN
      END
      SUBROUTINE SOLVE(TMG,XPG,HEDIX,FPG,NNODE)
      DIMENSION TMG(30,3),XPG(30),HEDIX(30),FPG(30,3)
      DO 5 I=1,NNODE
      DO 5 J=1,3
5     FPG(I,J)=0
      FPG(1,1)=TMG(1,2)
      FPG(1,2)=TMG(1,3)/FPG(1,1)
      FPG(1,3)=XPG(1)/FPG(1,1)
      DO 10 I=2,NNODE
      II=I-1
      FPG(I,1)=TMG(I,2)-TMG(I,1)*FPG(II,2)
      FPG(I,2)=TMG(I,3)/FPG(I,1)
10    FPG(I,3)=(XPG(I)-TMG(I,1)*FPG(II,3))/FPG(I,1)
      HEDIX(NNODE)=FPG(NNODE,3)
      NI=NNODE-1
      DO 20 I=1,NI
      II=NNODE-I
      III=II+1
20    HEDIX(II)=FPG(II,3)-FPG(II,2)*HEDIX(III)
*     DO 50 I=1,NNODE
*     DO 50 J=1,3
* 50  WRITE(6,110)FPG(I,J),HEDIX(I)
* 110 FORMAT(3X,2(E9.3,3X))
      RETURN
      END
      SUBROUTINE ERROR(HEDIX,HEDIL,IE,ERR1,ERR2,NNODE)
      DIMENSION HEDIX(30),HEDIL(30)
      DO 5 I=1,NNODE
      TTT=ABS(HEDIX(I)-HEDIL(I))
      TTTT=ERR2*HEDIX(I)
      TT=ERR1+ABS(TTTT)
      IF(TTT.GT.TT)GO TO 10
5     CONTINUE
      IE=0
      GO TO 15
10    IE=1
15    RETURN
      END
      SUBROUTINE OUT(TI,Z,HEDIX,NT,NL,NNODE,TETIX)
      DIMENSION Z(30),HEDIX(30),TETIX(30)
      DO 11 I=1,NNODE
      H=-HEDIX(I)
      HH=29.484
      WRITE(6,111)
      FORMAT("00")
      IF(H.GT.HH)GO TO
      TETIX(I)=.4591-.02732*LOG(H)
      GO TO 11
```

```
* 6        TETIX(I)=.6829-.09524*LOG(H)
* 11       CONTINUE
          WRITE(6,20)TI,NL,NT
          WRITE(6,150)
          WRITE(6,200)(I,Z(I),HEDIX(I),TETIX(I),I=1,NNODE)
  20       FORMAT(//,10X,"TIME= ",1X,F8.5,4X,"NL= ",I5,4X,"NT= ",I5)
  150      FORMAT(/,4X,"NNODE",8X,"COORDINATE",7X,"PRESSURE HEAD",
     1     7X,"WATER CONTENT")
  200      FORMAT(4X,I4,9X,F8.3,10X,F8.3,10X,F8.3)
           RETURN
           END
 OR--
   125.     .40     .0100    .1       .00001  1.0      25    015   10
   1
   1
   -159.19
   1
   .0      00.      0.        0.       0.        00.       .4        .400E-0726
   0    .50     .001     0      4      1      0
   0     0     0.          1       1     -14.495 -159.19 0
   0.00
   00
 OR--
```

UNSATURATED FLOW AND TRANSPORT

```
 XL= 125.000    TIME=      .400     TIVAL=.100E-01    TIMAX=       .100
 TIMIN=.100E-04    W=     1.000     NELEM=    25    NTM=    15    NST=   10
      1              .000
      2             5.000
      3            10.000
      4            15.000
      5            20.000
      6            25.000
      7            30.000
      8            35.000
      9            40.000
     10            45.000
     11            50.000
     12            55.000
     13            60.000
     14            65.000
     15            70.000
     16            75.000
     17            80.000
     18            85.000
     19            90.000
     20            95.000
     21           100.000
     22           105.000
     23           110.000
     24           115.000
     25           120.000
     26           125.000

 HO=-159.190
      1          -269.169
      2          -257.451
      3          -244.426
      4          -236.174
      5          -225.972
      6          -216.303
```

EVALUATION AND DESIGN OF DRAINED LOW-LEVEL RADIOACTIVE DISPOSAL SITES

FINAL REPORT

PROJECT E25-645, CONTRACT NO. DE-AS07-83ID12449

edited by

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Project Director

submitted to

U.S. DEPARTMENT OF ENERGY
Idaho Operations Office
Idaho Falls, ID 83401

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CONTENTS

LIST OF FIGURES

SUMMARY

Low-level waste disposal in shallow trenches has been the subject of much critical assessment in recent years. Historically most trenches have been located in fairly permeable settings and any liquid waste stored has migrated at rates limited mainly by hydraulic effects and the ion exchange capacity of underlying soil minerals. Attempts to minimize such seepage by choosing sites in very impermeable settings lead to overflow and surface runoff, whenever the trench cap is breached by subsidence or erosion.

The work undertaken in the project described in this report was directed to an optimum compromise situation where less reliance is placed on cap permanence, any ground seepage is directed and controlled, and the amount of waste leaching that would occur is minimized by keeping the soil surrounding the waste at only residual moisture levels at all times .

Measurements have been conducted to determine these residual levels for some representative soils, to estimate the impact on waste migration of mainly unsaturated flow conditions, and to generate a conceptual design of a disposal facility which would provide adequate drainage to keep the waste from being exposed to continuous leaching by standing water. An attempt has also been made to quantify the reduced source terms under such periodic, unsaturated flow conditions, but those tests have not been conclusive to date.

It was found that with adequate drainage, in most locations, moisture concentrations around the waste material will rarely rise appreciably above the residual level, thus reducing the waste leach rate substantially, compared with that calculated for saturated conditions.

It is evident that for relatively permeable or loosely-packed backfill the installation of a drainage layer may substantially reduce the environmental impact from dissolved waste materials. For low-permeability, clay-rich soils in tight compression, the reduction in ambient moisture levels around the waste may not be sufficient to justify the added cost and complexity of installing the drainage system. However, for most other situations, the resultant minimization of the source term may result in substantial projected dose reductions. None of the technology involved is novel as such nor does it call for unusual skills.

For low-permeability soils the waste should be placed about 30 cm (1 ft.) above the saturated layer formed by suction forces immediately above the gravel layer.

Since most disposal sites, even in humid regions of the United States, are exposed only to intermittent rainfall and as most trench designs incorporate some gravel base for drainage, the results of this project have broader applications in assessing actual migration conditions in shallow trench disposal sites. Similar considerations may also apply to disposal of hazardous wastes.

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Some of the work was shared with a parallel project conducted for the Savannah River Laboratory.

INTRODUCTION

Shallow land burial of low-level radioactive wastes has been practiced since the early days of the U.S. Atomic energy program. Unfortunately, early disposal sites were only required to meet "maximum permissible concentration" standards for any nuclear facility effluents and very little control was exerted on site inventory and waste form. As a consequence, many of those sites contained liquid wastes which seeped into the ground, where they were retained primarily by ion exchange and adsorption processes on mineral surfaces to the extent possible. The appearance of low levels of radioactive materials, especially tritium, in groundwaters offsite drew public attention to disposal conditions that were insufficiently controlled by more recent standards and as a consequence waste disposal of low-level waste was looked on by the public with some disfavor as a potential source of contamination of groundwater. To meet these objections the U.S. Nuclear Regulatory Commission has issued guidelines, under Title 10 Code of Federal Regulations Part 61, that prescribe waste form characteristics and site suitability criteria. Performance objectives are stated in terms of annual dose limits to the general public via all environmental pathways. The U.S. Environmental Protection Agency, also, is in the process of specifying effluent concentration levels, under Hazardous Waste Regulations (40CFR 122,265) or the Resource Conservation and Recovery Act (RCRA), that again must meet specific calculated population dose values. Both types of objectives must be met by selection of appropriate waste forms, source term control by reducing water flow, and control of effluent movement by appropriate site geology.

In either case, performance assessment depends on a good understanding of the mechanisms that govern mobilization and migration of the waste materials through soil or fractured rock into any significant aquifer, since groundwater transport is the only feasible pathway, other than deliberate or accidental intrusion, by which the waste materials can return to the accessible environment. Most of the calculational models described in the literature assume that sooner or later water infiltrates the burial trench, saturates the soil, leaches some of the waste at a rate controlled mainly by solubility considerations, and that the dissolved waste travels with the water, subject to retardation by surface adsorption on surrounding minerals, until an aquifer is reached, through which in due course it may reach the surface, in springs or wells, to enter the food chain.

Control of this process, in 10CFR61 and related documents, is envisaged primarily by four precautions: 1. use of a solid waste form, that, hopefully, is not excessively subject to dissolution; 2. waste emplacement preferably well above the water table; 3. use of an impermeable soil formation to minimize water flow towards the aquifer; and 4. installation of a stable impermeable trench cap to inhibit or retard water infiltration into the trench.

These approaches are illustrated in Figures 1 and 2 (Refs. 1 & 2) which illustrate diagrammatically the main elements of such a trench. In Figure 1 additional lining is introduced to contain water in the trench.

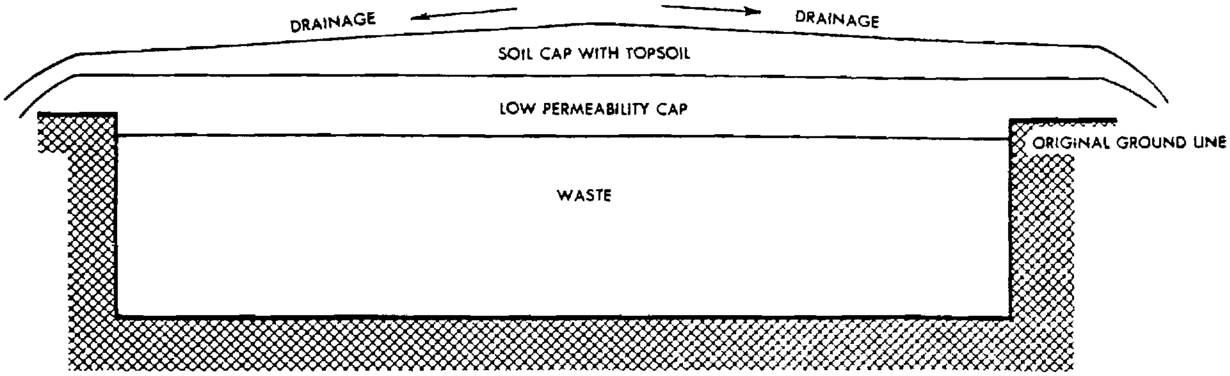
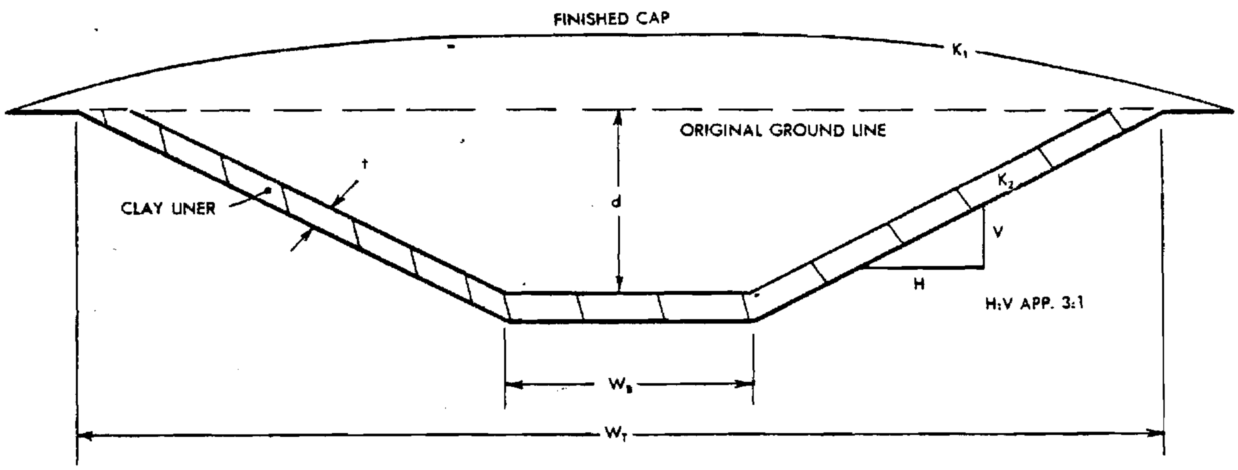


Figure 1a Closed trench with soil cap, showing cap drainage



H:V APPROXIMATELY 3:1
W_T = TOTAL WIDTH
W_B = BOTTOM WIDTH
K_1 = COEFFICIENT OF PERMEABILITY FOR FINISHED CAP
K_2 = COEFFICIENT OF PERMEABILITY FOR LINER
d = DEPTH
t = THICKNESS
V = VERTICAL
H = HORIZONTAL

Figure 1b Clay bottom liner (Ref. 1)

Fig. 1 Trench Configurations

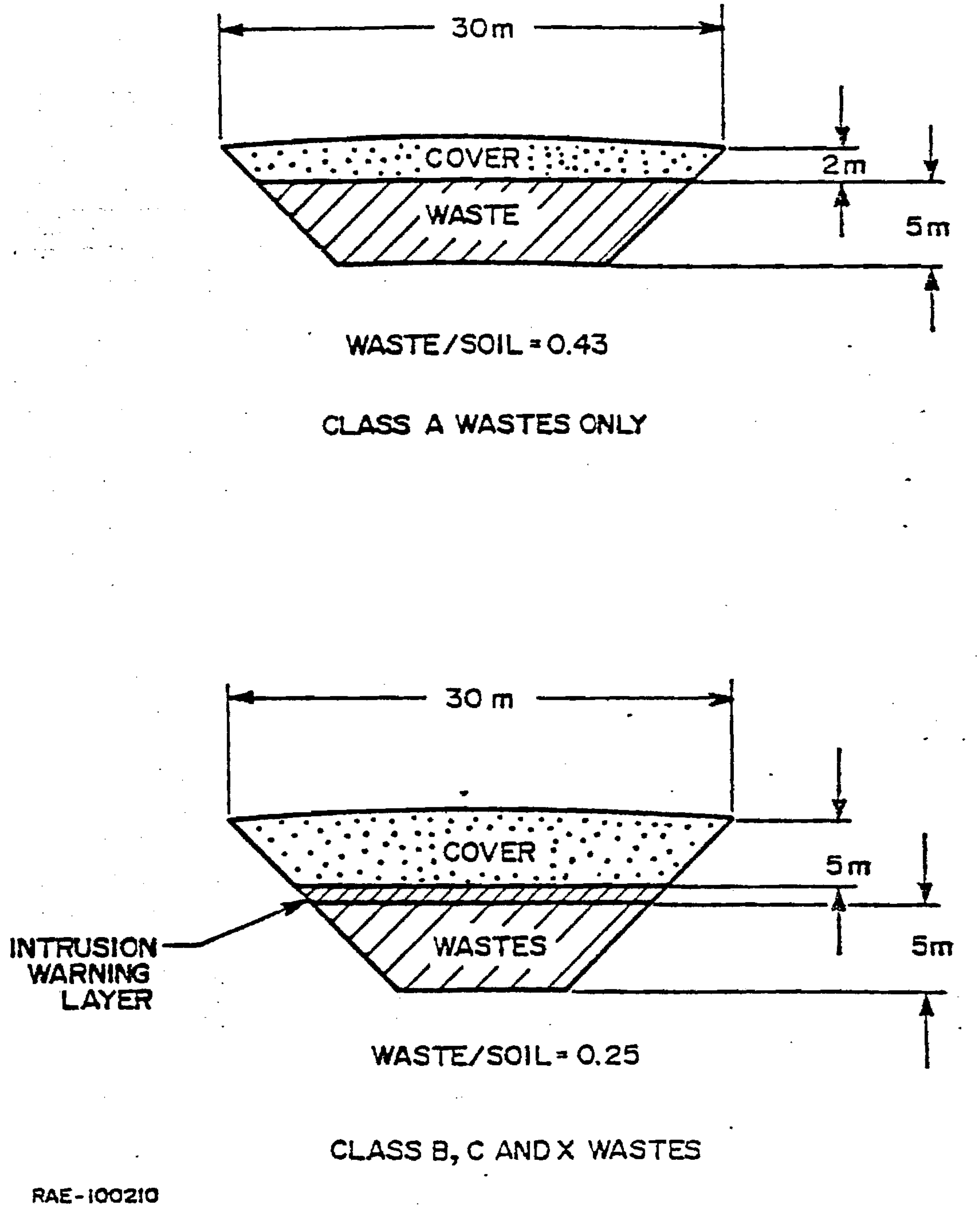


Figure 2 Trench designs for shallow aquifer and arid site (Ref. 2)

Figure 2 also shows a possible warning layer "to deter intruders". Short of actually concreting the walls or the trench bottom, some seepage ultimately will occur with a plume following the hydraulic gradient in the water table (Fig 3, from Ref.3). Figure 4 (Ref.3) illustrates the actual construction of some shallow trenches.

Several problems can arise in this approach. First of all, the trench cap will tend to collapse or erode in time, due to consolidation or compaction of the waste materials and the interstices between them, settling of backfill soil, and the effect of surface water. This means that sooner or later water will enter the trench unless very elaborate cap structures are devised. Figures 5 and 6 give examples of such cap designs, which add enormously to the cost of disposal and are almost equivalent to the surface-bunker retrievable-storage concept.

The second problem arises from the fact, that with a highly impermeable base formation any infiltrated water in the trench has nowhere to go and sooner or later will fill the trench and overflow. This "bath tub effect" has been observed at some sites and results in surface flow of trench water, instead of downward seepage towards the water table, and an early return to the accessible environment of potentially contaminated water. In addition, the waste would find itself engulfed by standing water so that any leaching effects would be greatly increased. Abatement of the bath tub effect by reliance on even more elaborate cap structures is questionable and expensive, particularly since there is no guarantee that lateral inflow into the trench would not occur. McCray et al. (Ref.5) have reported observations on such interflow.

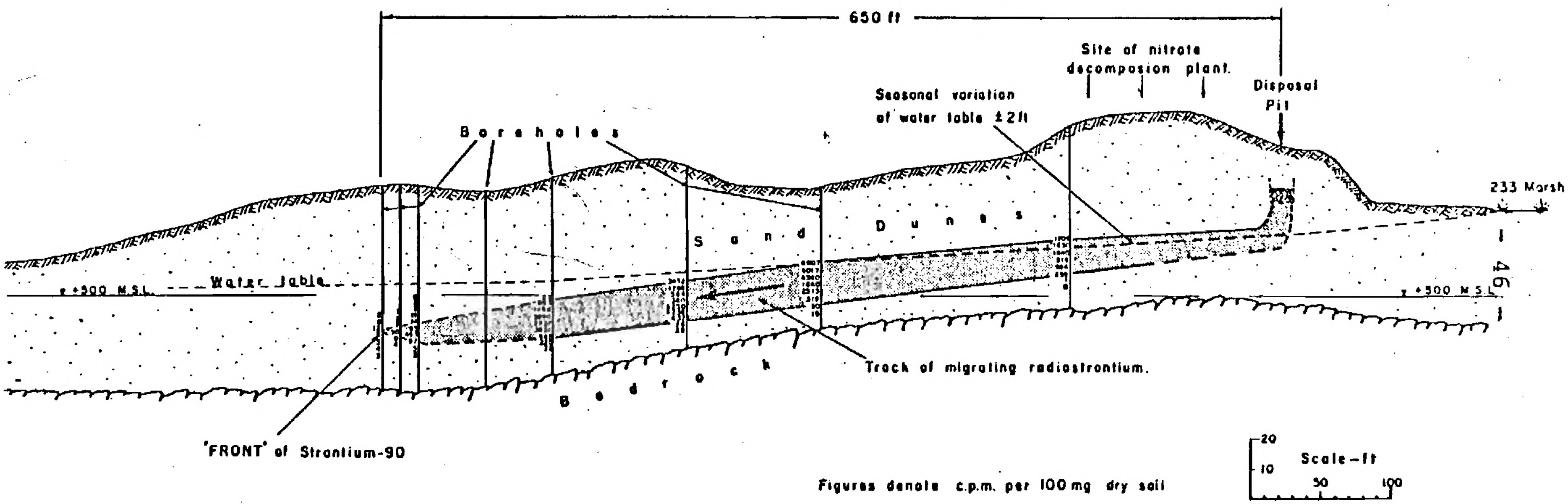
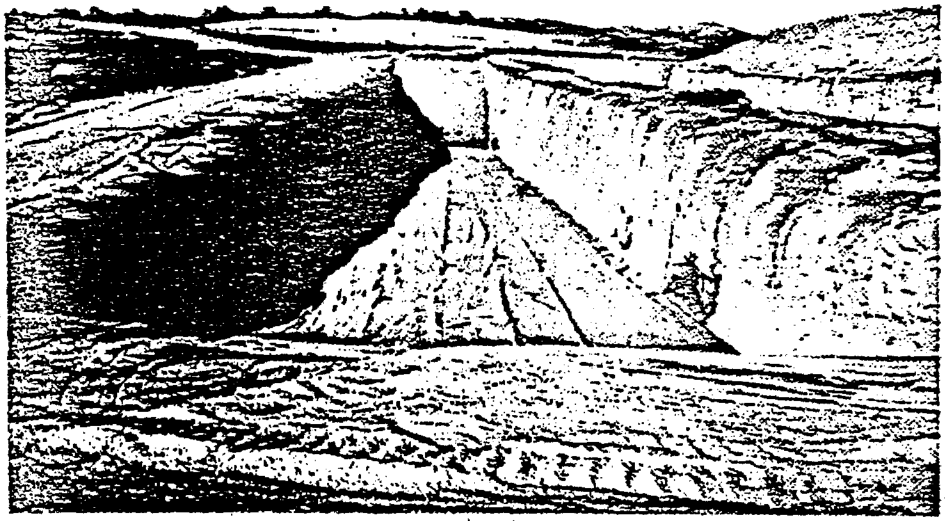
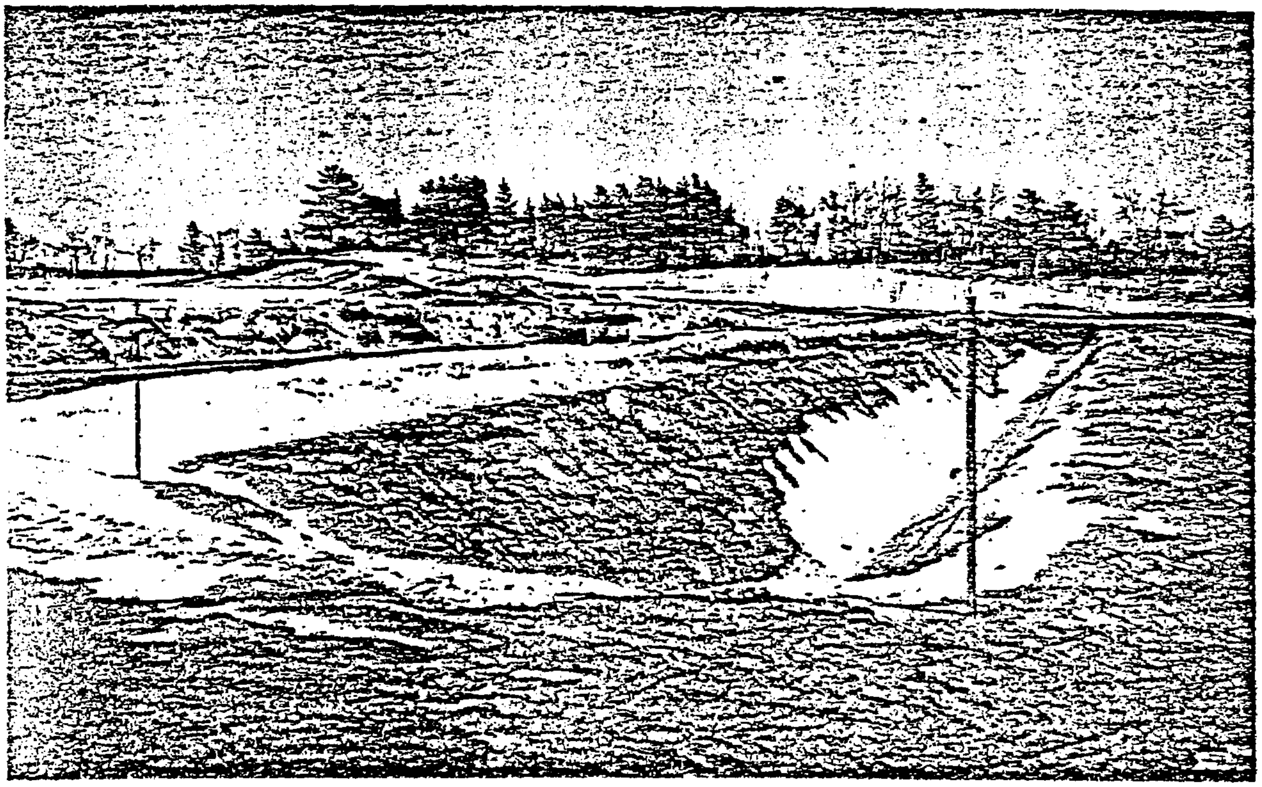


Figure 3 Section along track of migrating radionuclides (Ref 3)



Waste Burial Pit at the Los Alamos Scientific Laboratory (New Mexico, USA) Dug into Tuff (180 x 15 x 8 m Deep). Note Steep Slope and Relatively Clean Cut Walls [11]



A Trench Dug into Sand in Area "C" at CRNL Showing Shallow Sloped Walls

Figure 4 Views of two burial sites (from Ref. 3)

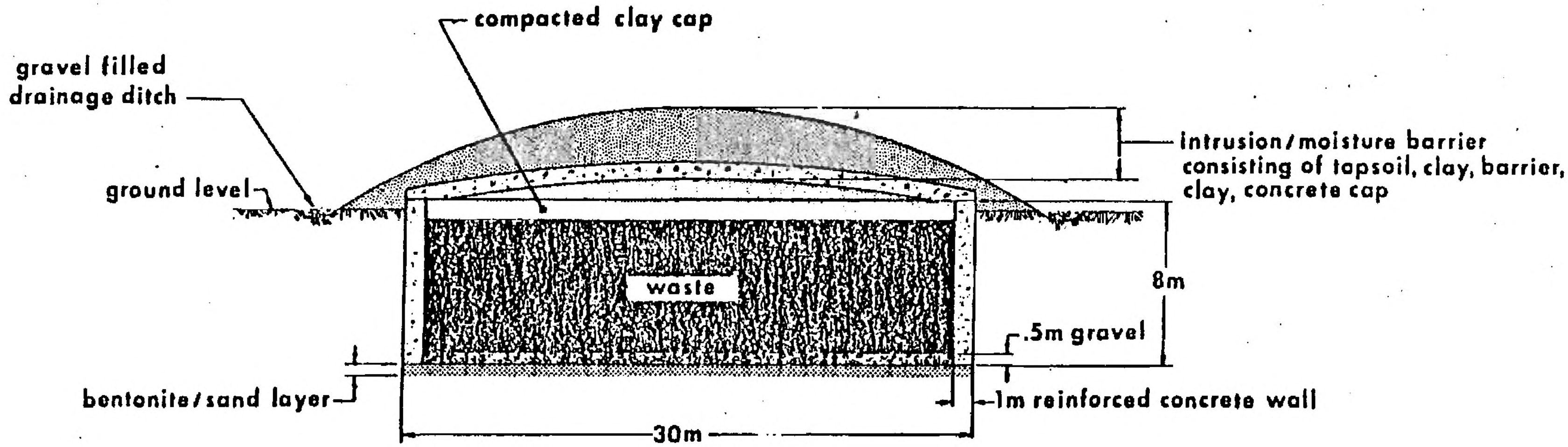


Figure 5 Cross section through concrete vault facility (Ref. 3)

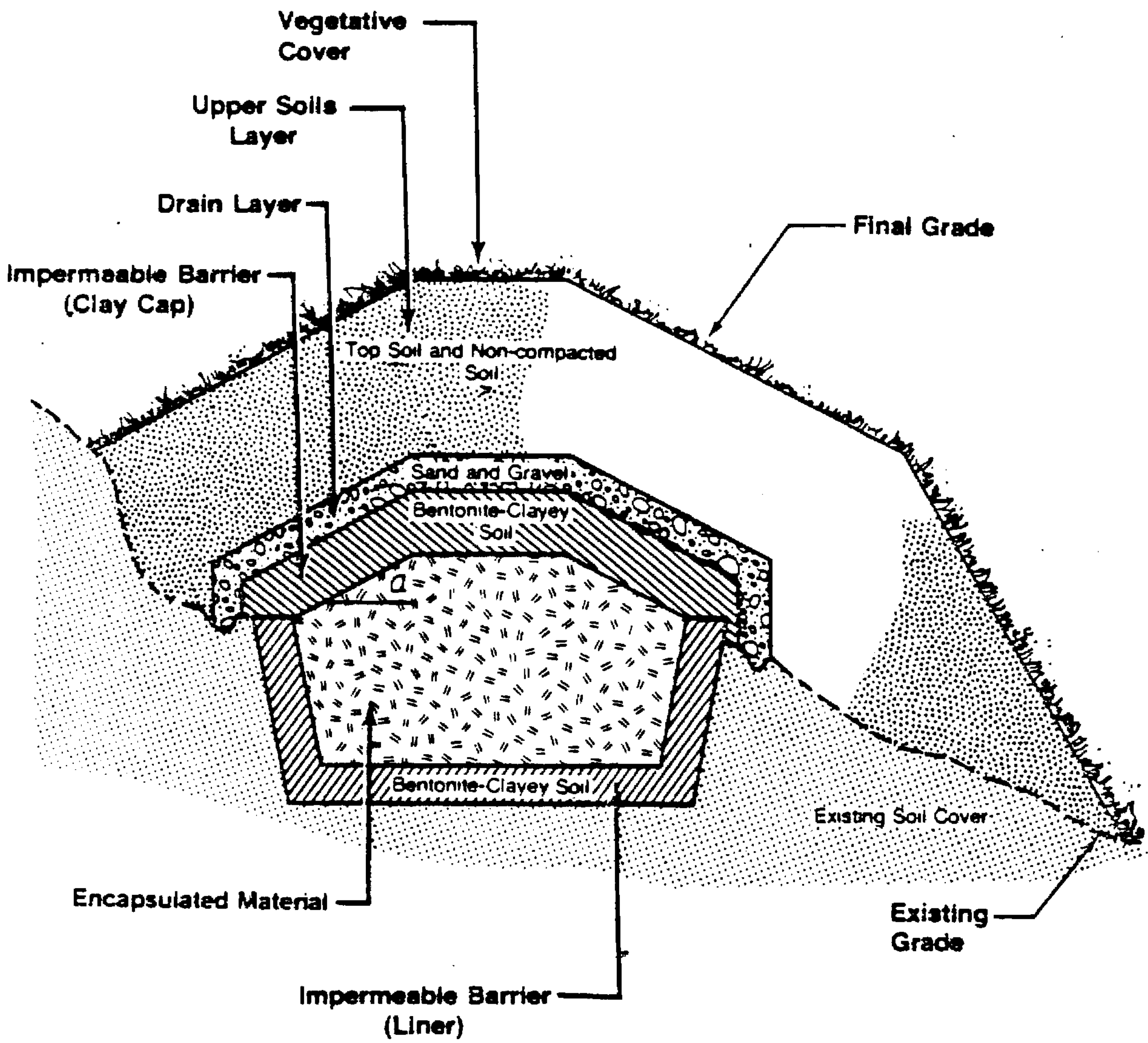


Figure 6 Profile of encapsulation and cover - Canonsburg site (Ref. 4)

a – Slope Angle

An alternative way of dealing with the threat of a bath tub effect is by the installation of drains, combined in some cases by deliberate pumping from the trenches. This approach is illustrated in Figure 7 (Ref. 2), where the pump well is also used for monitoring purposes, and has been proposed for the Central Disposal Facility at Oak Ridge for hazardous wastes (Ref. 6). For the Canonsburg site, Metry et al. (Ref. 4) also propose a near-surface drain to minimize infiltration, see Figure 8.

In the work described in this report this approach has been taken a stage further by allowing the drained-off water to seep into the ground along a predetermined seepage path. This eliminates the need for active pumping which would normally be impractical after closure of the site. By also selecting conditions promoting easy drainage, one also minimizes the amount of moisture in contact with the waste, so that leaching effects may be greatly reduced, resulting in a much smaller source term for any hazard prediction. This project has been concerned with studying the effects of avoiding high water content in the waste area on leach effects and model calculations and with a consideration of conceptual designs for this approach.

A preliminary account of this work was presented at the DOE Participants Meeting in Denver in September, 1984 (Ref. 7).

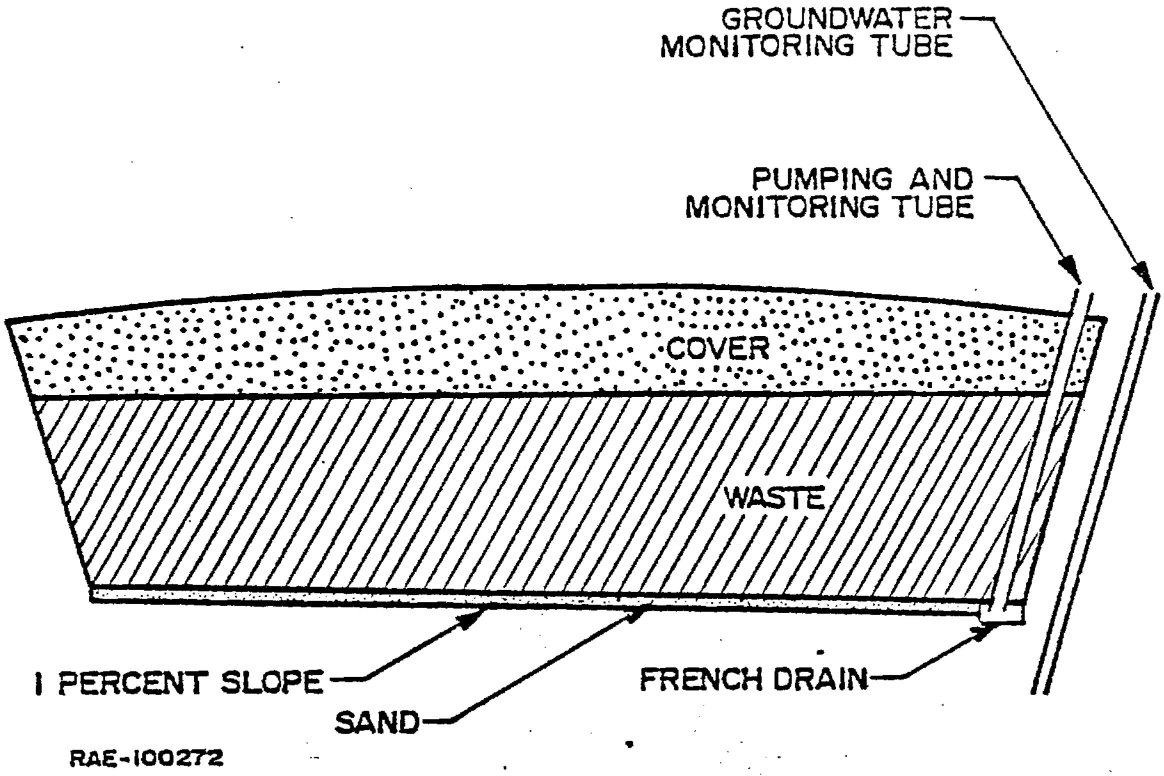


FIGURE 7-a. CROSS SECTION OF TYPICAL TRENCH

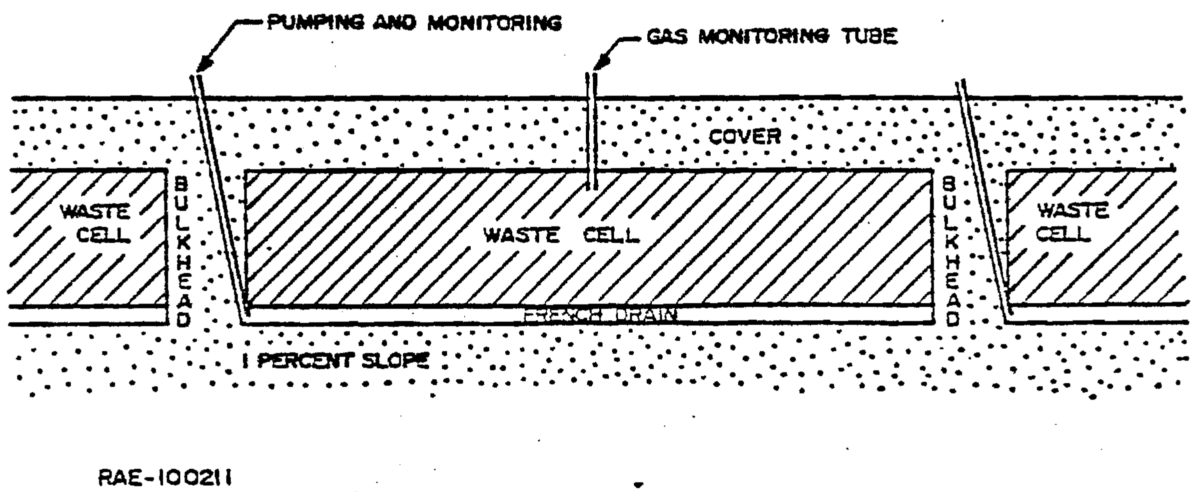


FIGURE 7-b. SECTION OF TYPICAL TRENCH ALONG ITS LONG AXIS

Figure 7 Sections of typical drained trench (Ref. 2)

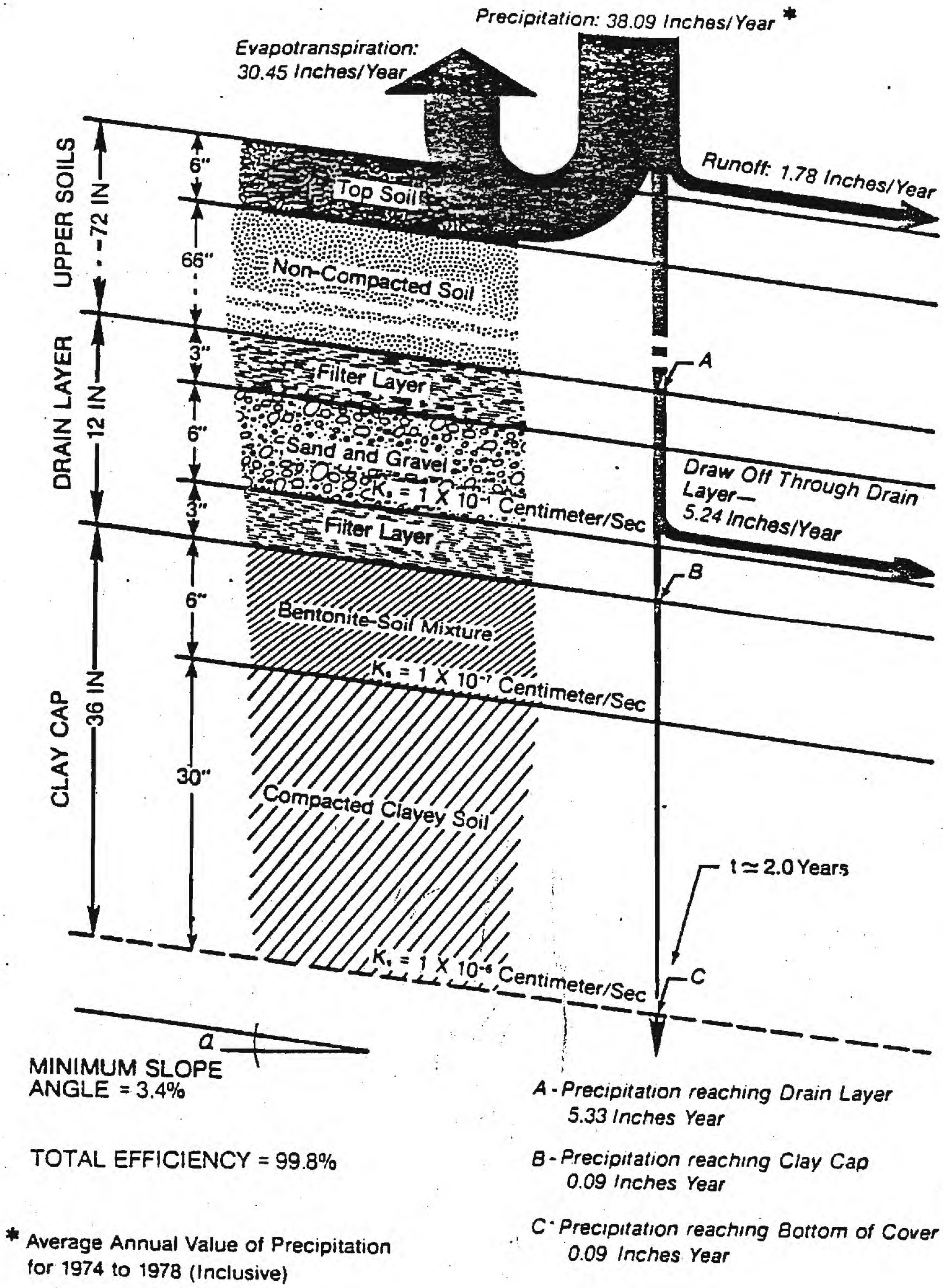


Figure 8 Water budget for cover system - Canonsburg site (Ref. 4)

TRENCH HYDROLOGY

The hydrology of a burial trench is shown diagrammatically in Figure 9. A very high proportion of precipitated water is returned to the atmosphere by evaporation and evapotranspiration and typically only 20-25% or less will actually infiltrate the trench itself. Once there, water movement is subject to a balance of gravitational and capillary forces, though for fairly permeable backfill surrounding waste packages it is reasonable to assume a slow, but steady net downward flow. As this flow passes the buried wastes it is usually assumed that some leaching i.e. decontamination of buried waste material by the passing flow of water, will occur and dissolution of some radioactive materials, that may then remain in solution or adsorb on any fine suspended particulates that may be present. Self-retention within the backfill soil presumably occurs, but is rarely included in any assessment model.

Although 10CFR61 assumes location of the trench in an impermeable medium, any impact assessment ordinarily takes the finite permeability of the surrounding soil for granted and accepts it as the normal pathway for the dissolved waste ions or complexes (9,10). Innumerable measurements have been reported on the resultant flow through such soil and on retardation effects on the migration of any dissolved ions due to sorption-desorption effects on any mineral surfaces in contact with the water flow (11-15). These processes are generally considered part of the engineered barriers of the system, but invariably are assumed to be subject to saturated flow.

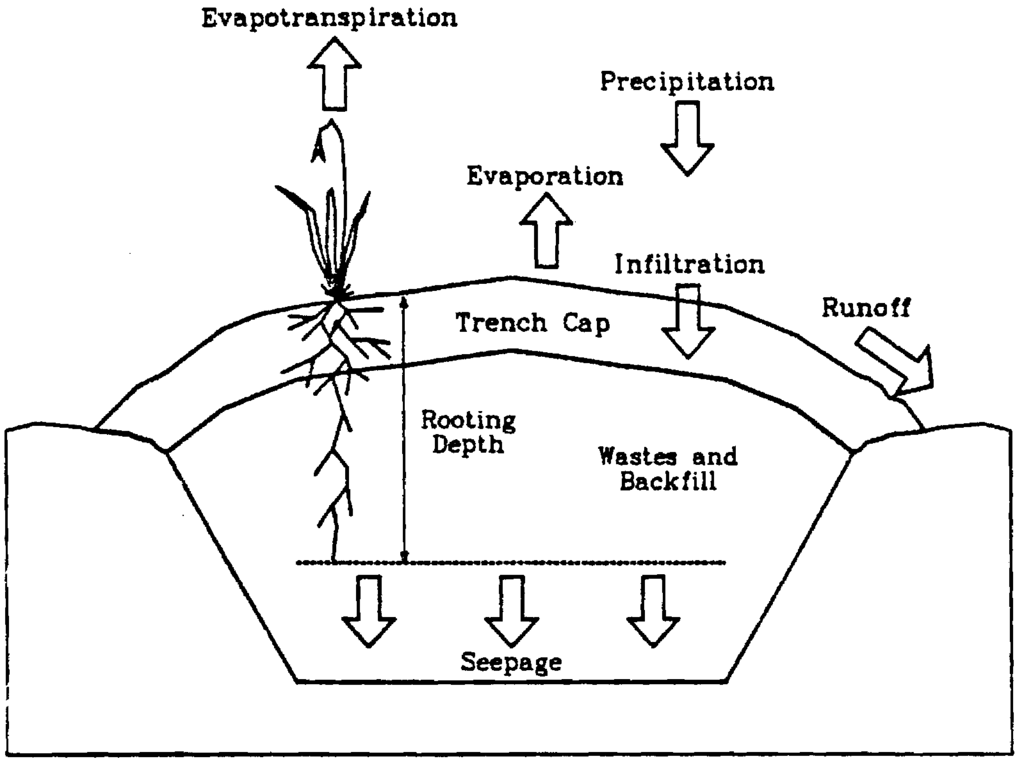


Figure 9 Hydrology of shallow land burial trench(from Ref. 7)

Actually, most soil systems will not be saturated unless the soil is unusually retentive or the water is allowed to back up, as in the bathtub situation (16). For arid sites in the Western U.S., soil saturation would be rare; this has been studied by the Los Alamos group (17-19). Figures 10 and 11 show variations in moisture profiles at Maxey Flats observed near the surface (0.9m) and at depth (2.4m). Strong seasonal variations are evident near the surface; a smooth curve exists at depth. In both cases moisture levels were well below saturation most of the time, though in the trench cap significant water retention occurred because of suction effects from its lower surface. Observations by Davis et al. (Fig. 12) also show that variations in the level of the water table following rainfall depend on rapid infiltration flow and only slow drainage rates (21). Thus, even in the "humid zone" of the Eastern United States unsaturated moisture conditions may prevail for much of the time, between heavy showers, as occur in the South, or during periods when the surface is frozen or snow-covered in the North. If the backfill and surrounding soils are fairly permeable, this implies that the waste may find itself in moderately dry surroundings much of the time and the time-averaged leach rate may be substantially different from that assumed for "conservative", saturated conditions. Some infiltrated water may perch on top of drums and packages or form puddles on plastic wrappings, but the volume available for such water is limited and often such water may be subject to syphon action through surrounding soil. In any case, any subsequent water flow will necessarily by-pass such occupied spaces. The present study was directed to investigate the benefits of reducing the ambient moisture levels around the waste as much as possible by accepting a periodic mode of infiltration and removing the major cause of water back-up.

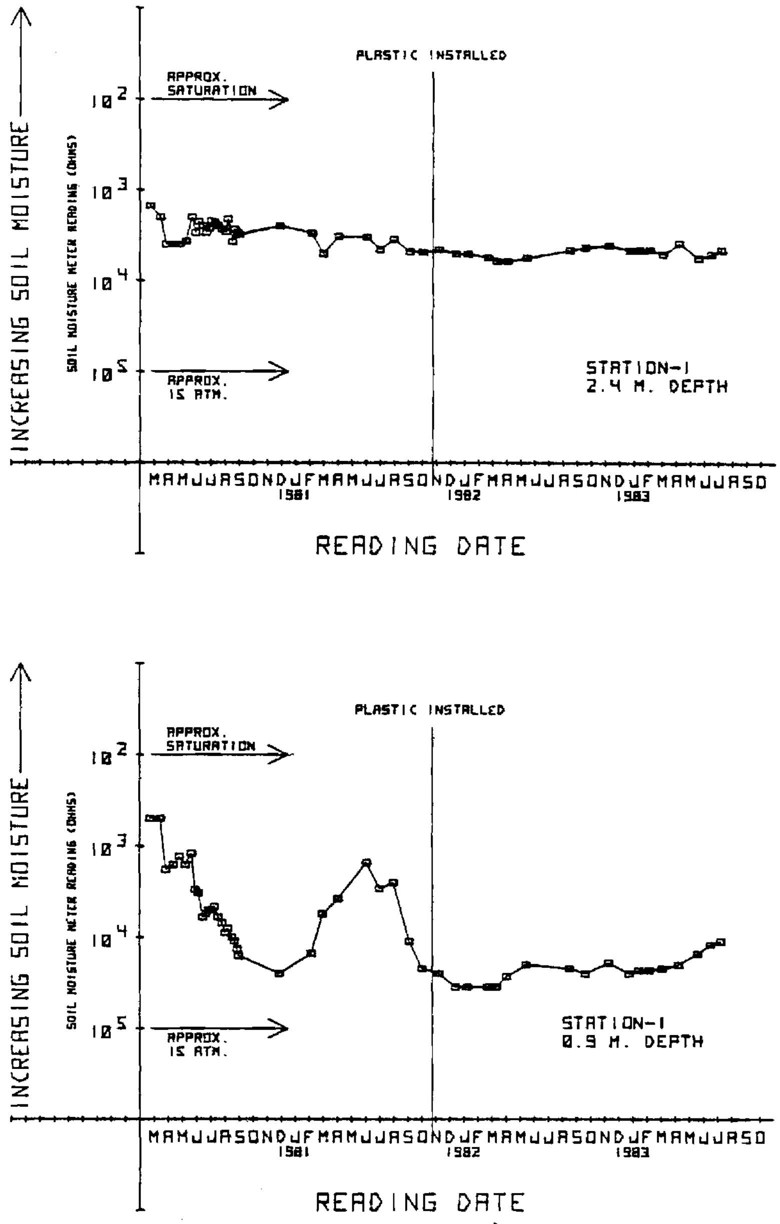


Figure 10 Soil moisture plots at Maxey Flats at two depths (Ref. 8)

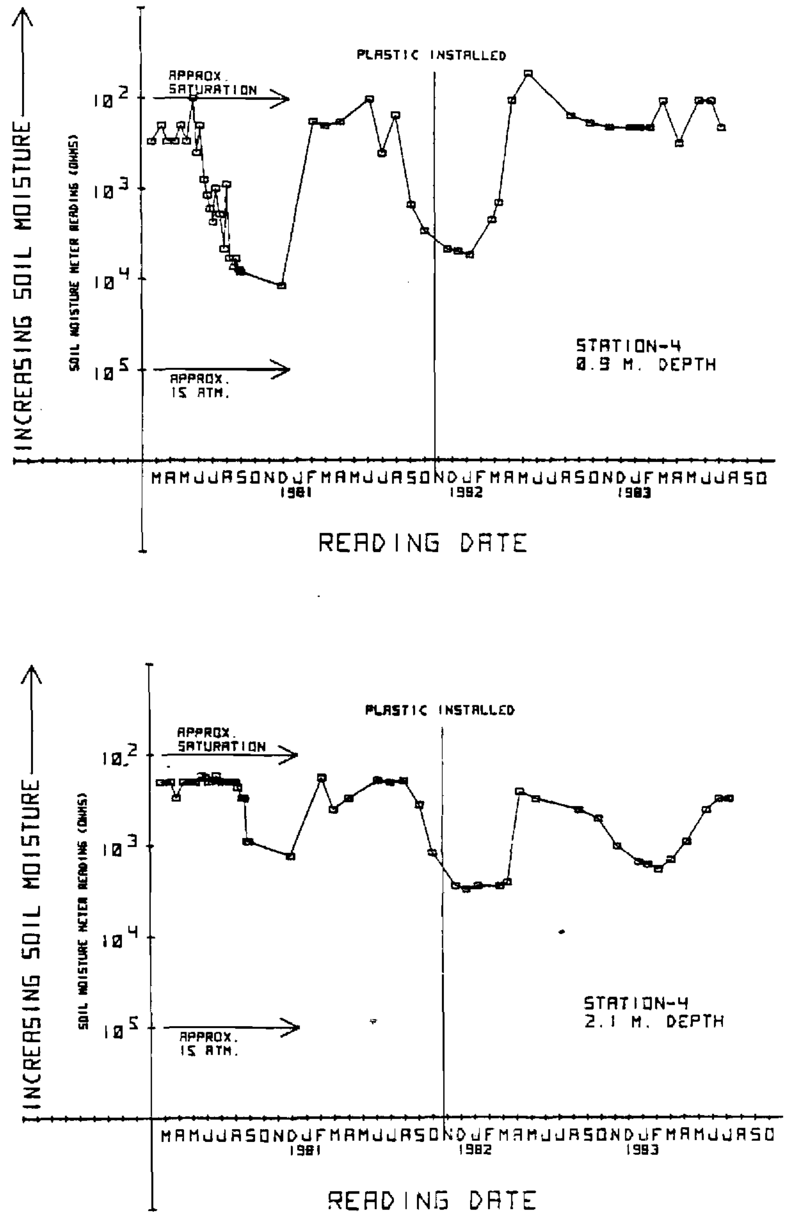


Figure 11 Soil moisture plots at two depths in a trench cap at Maxey Flats (Ref. 8)

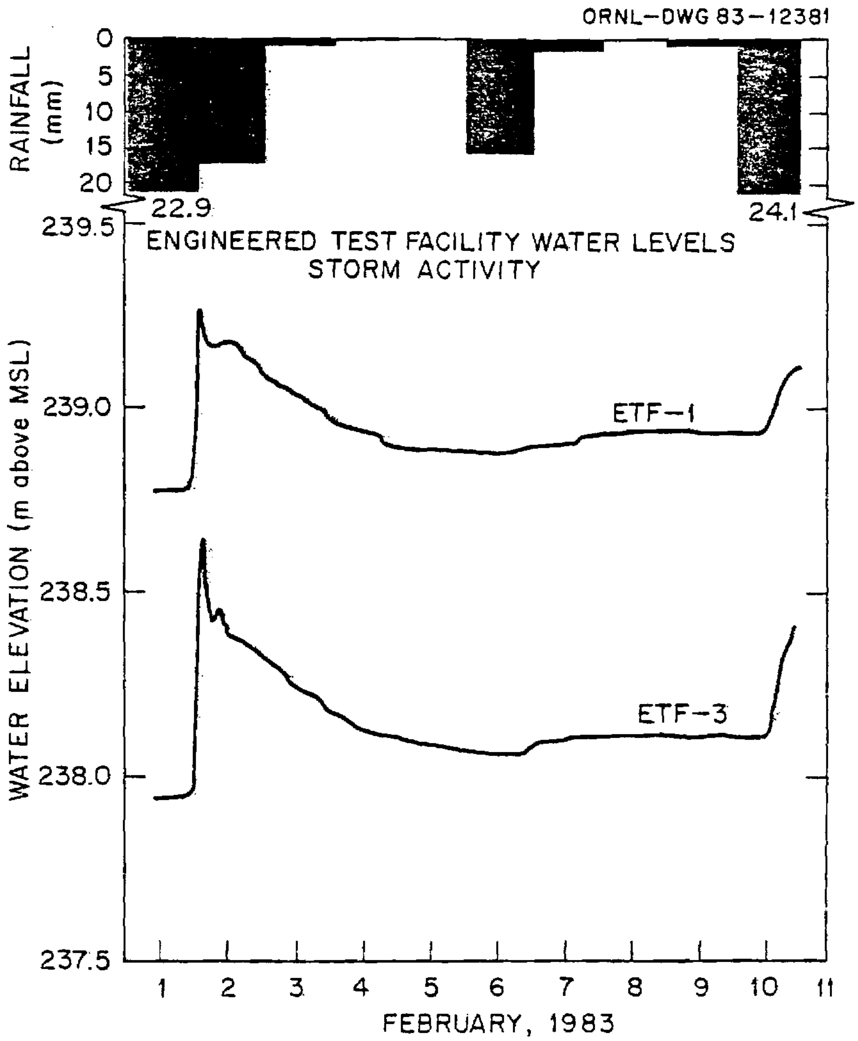


Figure 12 Groundwater response to rainfall for one week in February 1983 (Ref. 6)

Migration of dissolved wastes under unsaturated conditions is a fairly complex process. In a clay-rich soil not all of the water present in the soil is mobile, but may be bound in the clay structure. The mobile water may move slowly and would not fill all of the pores (22). As a result the volumetric flow rate for a given percent saturation value would not be proportional to the water content. As moisture content decreases the capillary force begins to predominate. This has two consequences:

1. Except in highly permeable, coarse materials, like coarse sand, the moisture level will reach a finite minimum residual moisture concentration, which depends on the hydraulic conductivity of the soil and, typically, its clay content, and which will be retained indefinitely at depths below those affected by evapotranspiration.
2. Above any major structural interface, a moist column will be retained by suction forces that may have a higher moisture content than the drained volume above. This leads to an effect of water flow around cavities, such as waste materials, reducing effectively the amount of water available for leaching. It also imposes a need to allow a soil layer above any built-in drain before emplacing wastes.

All of these effects have been studied in this project to the extent that they affect disposal trench design. The work undertaken in this project consisted of four main tasks:

a) Construction of a test bed to study the response of a soil column to steady or periodic infiltration under unsaturated flow conditions;

b) Development of a simple computer model to permit generalization of the data obtained;

c) Study of waste leaching conditions when exposed to unsaturated flow; and

d) Conceptual design of a shallow waste burial facility to minimize immersion of the waste material by the provision of drains and directing the off flow.

Various subsidiary tasks, such as characterization of soils, calibration of moisture probes, and code development benefited from parallel work going on under the sponsorship of the Savannah River Laboratory, EI Du Pont de Nemours & Co.

TEST BED CONSTRUCTION

One of the prime objectives of this investigation was the measurement and demonstration of flow and drainage conditions of representative soil columns under unsaturated conditions. Tests were also conducted on laboratory scale columns, but from the start it was considered essential to conduct field scale tests to minimize wall effects and drain interface effects.

The test bed was intended to be readily drained and to be accessible from one side to measure moisture profiles during the course of a run. It had to be easy to dismantle, capable of being layered if necessary, and subject to various methods of introducing water flow.

A site was chosen on a natural slope behind the Frank Neely Nuclear Research Center and the Electronics Research Building on the Georgia Tech Campus. Figure 13 is a sketch cross section of the trench. The bed itself consisted of a wooden box, 6ft high, 2 ft. x 2ft. in cross section which was installed in the trench cut whose walls had been lined with plastic sheet and braced. Figure 14 shows the major dimensions in plan. Figure 15 presents two stages in the construction of the trench and the installation of the test box. Some major problems were encountered in the construction and installation of the drain pan, which underwent several modifications. Similarly, experience led to various improvements in revetment of the trench walls and the sloping of the drainage bed at the bottom of the trench. The assistance of the Georgia Tech Physical Plant Department in cutting the trench and supplying gravel and other materials is gratefully acknowledged.

The front panel is removable for loading and unloading. Figure 16a shows a series of tensiometers that were installed to measure moisture profiles. The tensiometers were Soiltest Inc., Model 120; great care had to be taken in their installation to remove any residual air bubbles. It was found that the tensiometers were insufficiently responsive at low moisture concentrations and for that reason most later tests relied on electrical conductivity probes. Figure 16b shows the contact panel and meter for these probes on top of the test bed.

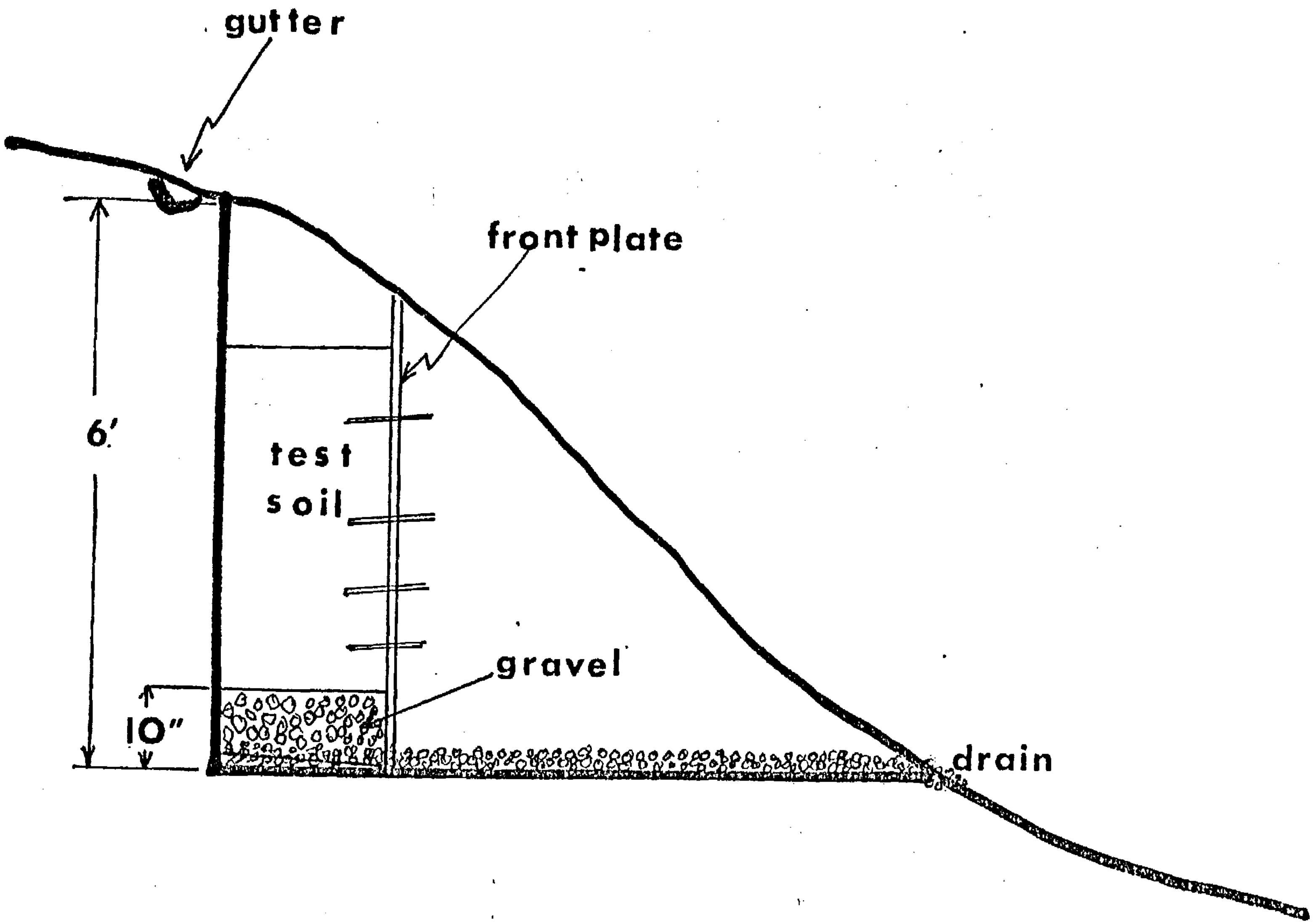


Figure 13 Cross section of Test bed trench

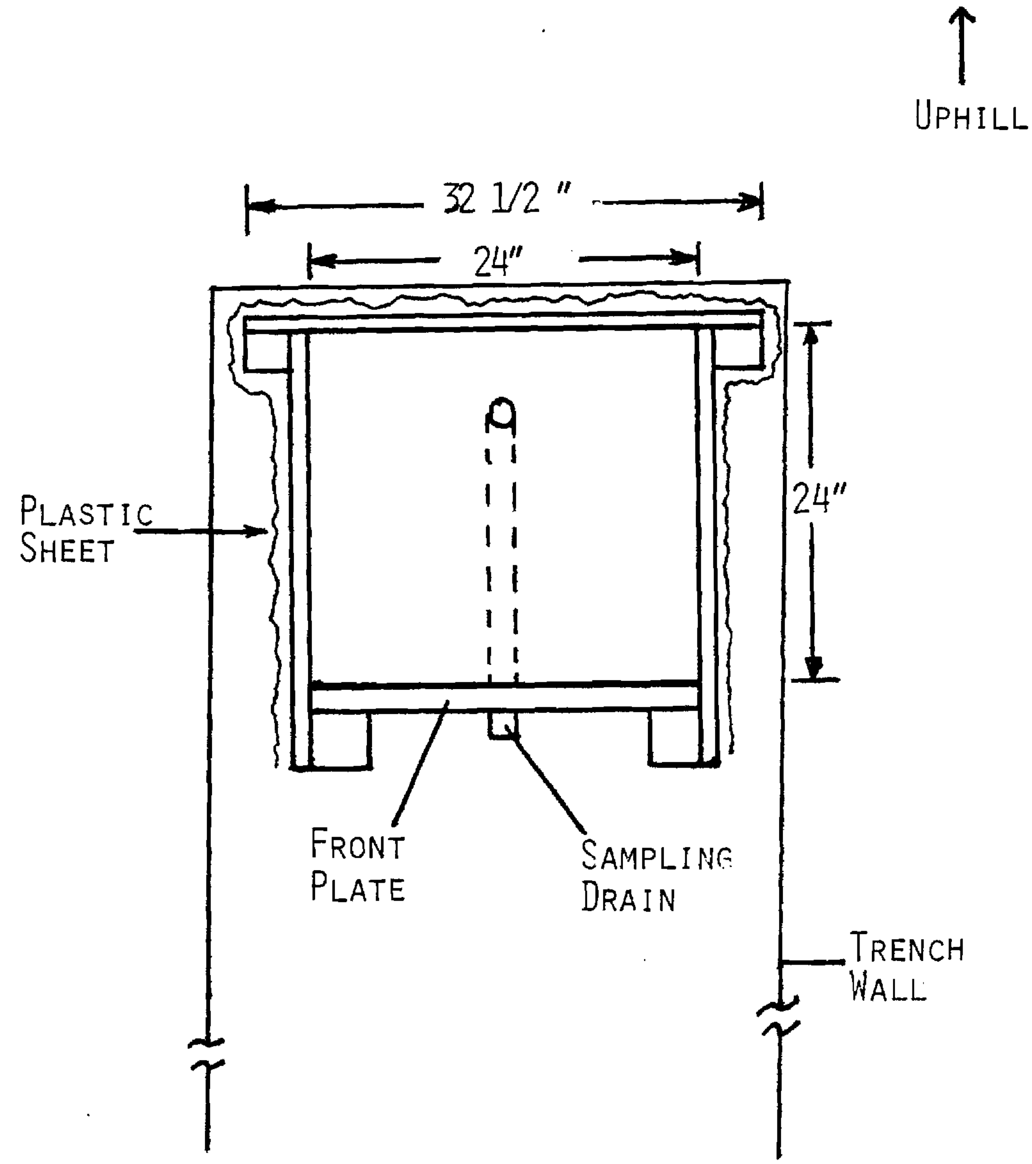


Figure 14 Sketch of test bed plan

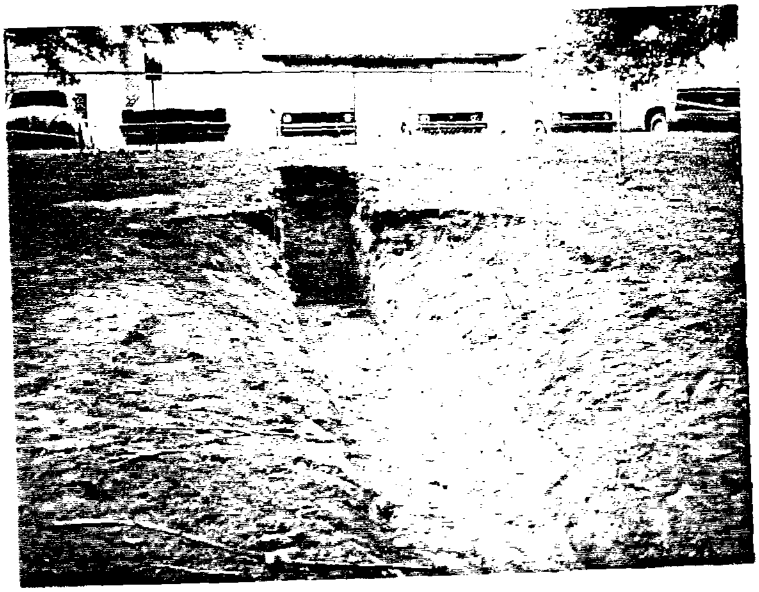


Figure 15 Views of test bed during construction

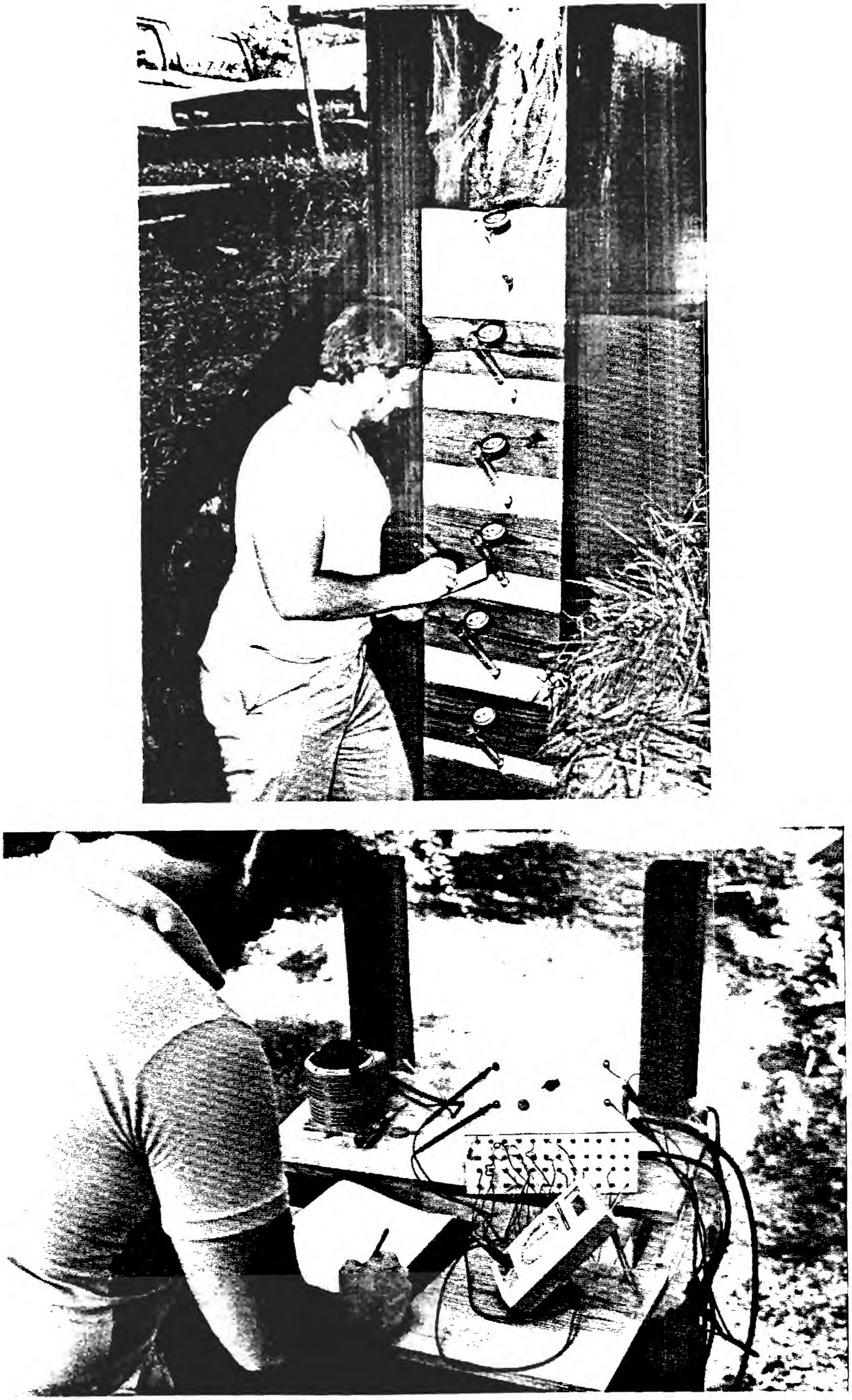


Figure 16 Views of instrumentation on test bed

MATERIALS

Test work was done with two types of sand, referred to as Rollo Sand and GT Sand, two types of fairly clayey soils, SRP No. 1 and No. 2, and a synthetic mixture, FP soil. These soils were selected to cover a range of soil-moisture conditions and to represent a variety of soils found at different existing sites. Table 1 lists the basic properties and composition of these soils.

TABLE 1 - SOIL PROPERTIES

SOIL TYPE	BULK DENSITY (g/cm^3)	POROSITY	SAND FRACTION (%)	SILT FRACTION (%)	CLAY FRACTION (%)	SATURATED HYDRAULIC CONDUCTIVITY (cm/day)
Rollo Sand	1.4.0	0.472	98.9	1.1	0.0	
G.T. Sand	1.38	0.479	97.4	2.6	0.0	2000
SRP #1	1.24	0.32	62.0	9.0	29.0	30
SRP #2	1.20	0.547	56.0	4.0	40.0	60
FP Soil	1.42	0.466	73.4	15.5	11.4	-

Particle size analyses were conducted and the distribution curves of the four soils under study were determined. The results are shown in Tables 2-5; Figure 17 shows the distribution curves of three of the soils.

Table 2 - PARTICLE SIZE DISTRIBUTION - G. T. SAND

DIAMETER	% PASSING	DIAMETER	% PASSING
(m)	(%)	(m)	(%)
1410.0	90.7	23.0	1.5
1000.0	80.7	13.0	1.5
707.0	65.8	9.3	0.7
500.0	46.6	6.6	0.7
250.0	10.4	5.0	0.7
105.0	2.9	3.5	0.0
75.0	2.6	2.7	0.0
36.0	1.5	1.3	0.0

TABLE 3 - PARTICLE SIZE DISTRIBUTION - ROLLO SAND

DIAMETER (μm)	% PASSING (%)	DIAMETER (μm)	% PASSING (%)
1410.0	86.0	36.4	1.2
1000.0	51.3	23.0	1.2
707.0	12.8	13.3	1.2
500.0	4.5	9.4	1.2
250.0	1.3	6.7	0.6
105.0	1.1	4.7	0.6
75.0	1.1	3.4	0.0

TABLE 4 - PARTICLE SIZE DISTRIBUTION - SRP #1

DIAMETER (μm)	% PASSING (%)	DIAMETER (μm)	% PASSING (%)
1410.0	97.1	7.6	30.4
1000.0	94.5	5.4	29.7
500.0	80.4	3.8	29.7
250.0	61.0	2.7	29.0
75.0	34.8	2.0	28.3
63.0	34.2	1.1	27.7
29.0	33.1	1.0	27.0
18.4	32.4	0.8	26.3
10.7	31.7	0.7	25.6

TABLE 5 - PARTICLE SIZE DISTRIBUTION - SRP #2

DIAMETER (μm)	% PASSING (%)	DIAMETER (μm)	% PASSING (%)
1410.0	97.1	16.5	42.3
1000.0	94.6	9.6	41.6
500.0	84.2	6.9	40.9
250.0	62.1	4.9	40.3
75.0	43.3	2.4	39.6
63.0	43.1	1.0	38.9
25.8	43.0		

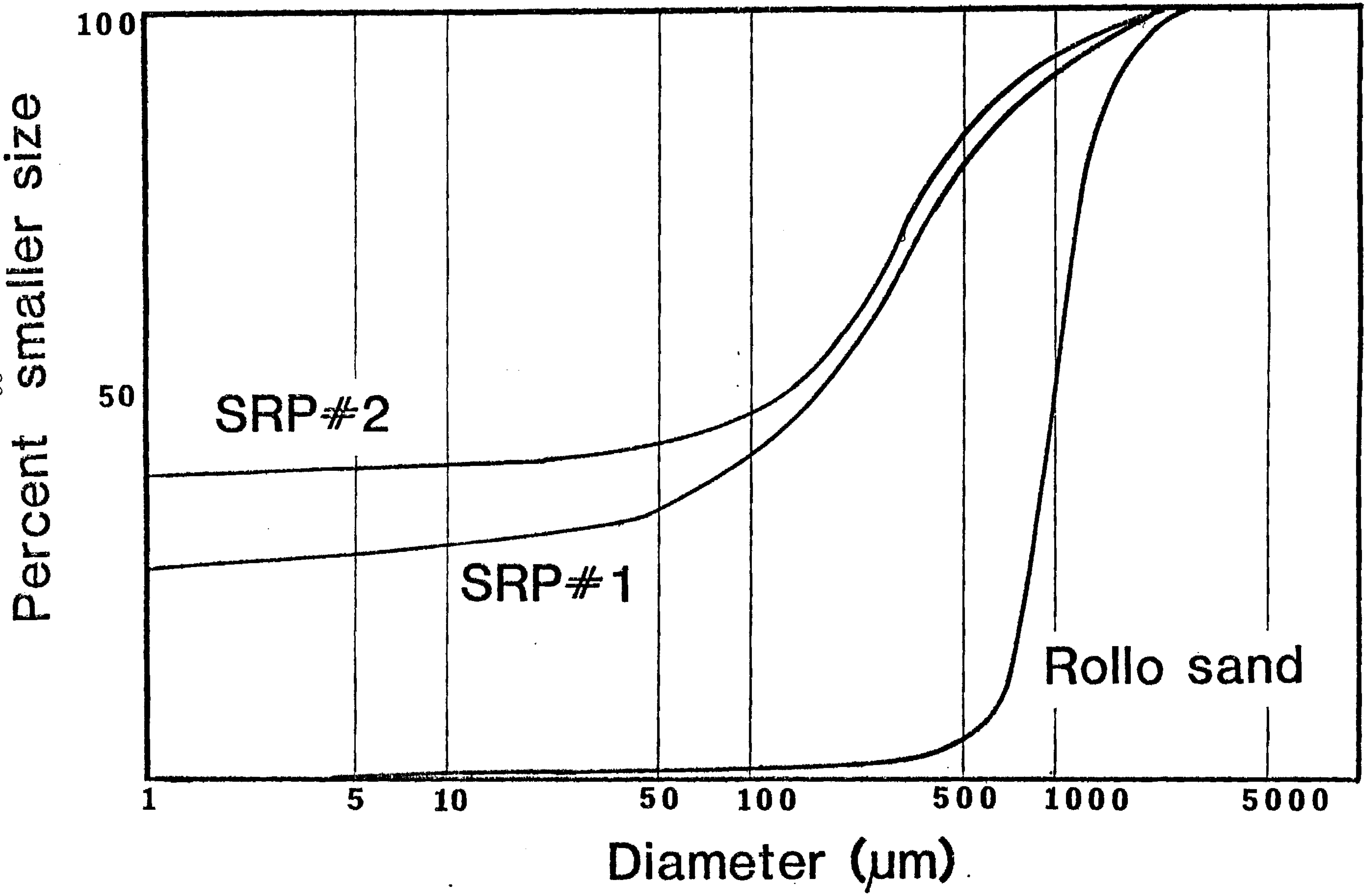


Figure 17 Particle size distributions

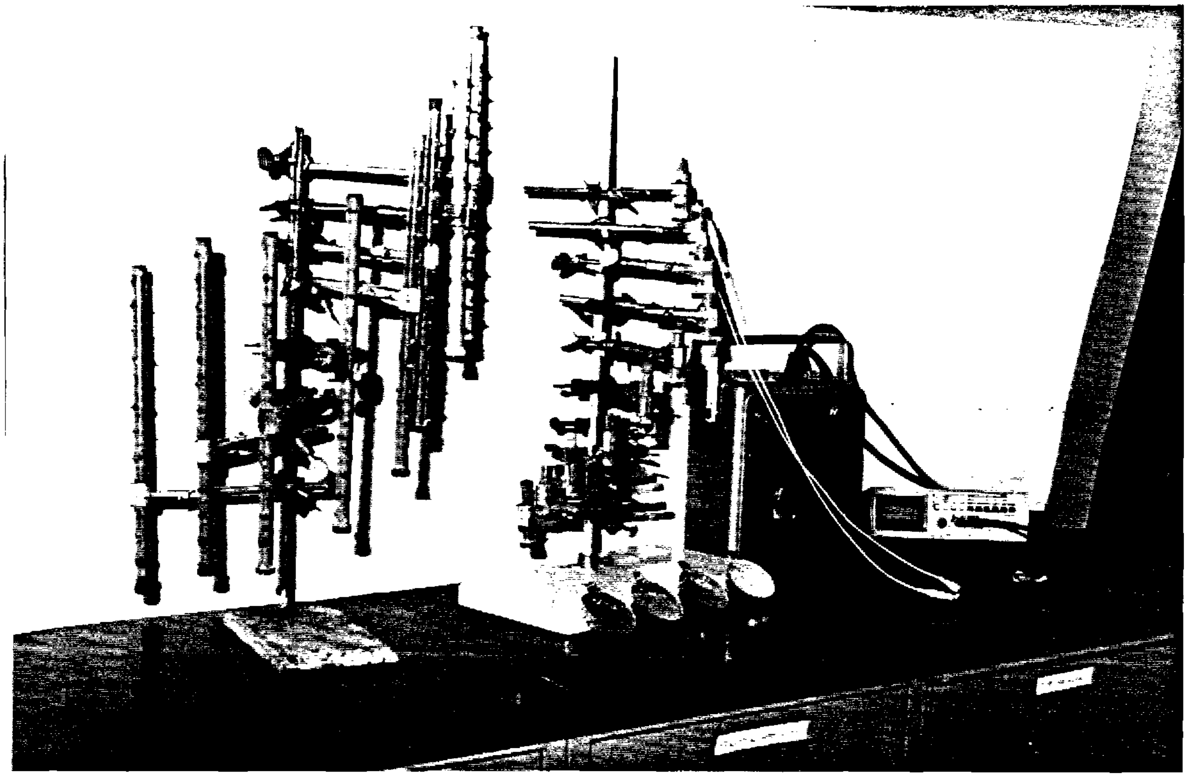
LABORATORY TESTS

Bench-scale tests were conducted to evaluate the basic properties of the soils, to measure residual moisture levels and to calibrate the conductivity probes for use in the test bed. Column tests were conducted in three sizes of tubes, which are shown in Figure 18. The short tubes, top right were employed mainly to obtain residual moisture contents, though care had to be taken to allow for the suction layer above the bottom screens. The other columns had built-in electrodes and were calibrated by direct weight-loss moisture determinations. The larger columns, Fig 18c, have been used for hydraulic conductivity measurements and for radiotracer tests.

Figures 19-21 present electrode calibration curves, plotting electric resistance between adjoining electrodes versus percent saturation, for GT sand and the two SRP soil samples. Similar curves have been obtained for the other soil materials. For consistent results, care had to be taken to ensure even packing and the column had to be presaturated to remove any remaining air. The calibrations for the various columns were consistent, but in practice the electrodes had to be recalibrated for the large test bed.

Since the purpose of the project was to minimize soil water content surrounding the waste material, it was important to measure how low a moisture content could be obtained by draining. Due to capillarity effects all soils will retain a minimum moisture content once water has infiltrated, with the amount retained dependent on pore size, surface wetability and clay content.

Table 6 shows the results of a series of tests on sized sand columns. As expected, the finer sizes (large mesh number) retain more water in their smaller pores. Table 7 compares the residual water content for two sands and two SRP soils, whose size distribution was shown in Figure 17. Again, as expected, the SRP soils with their high clay content and fine size components show relatively high residual water values.



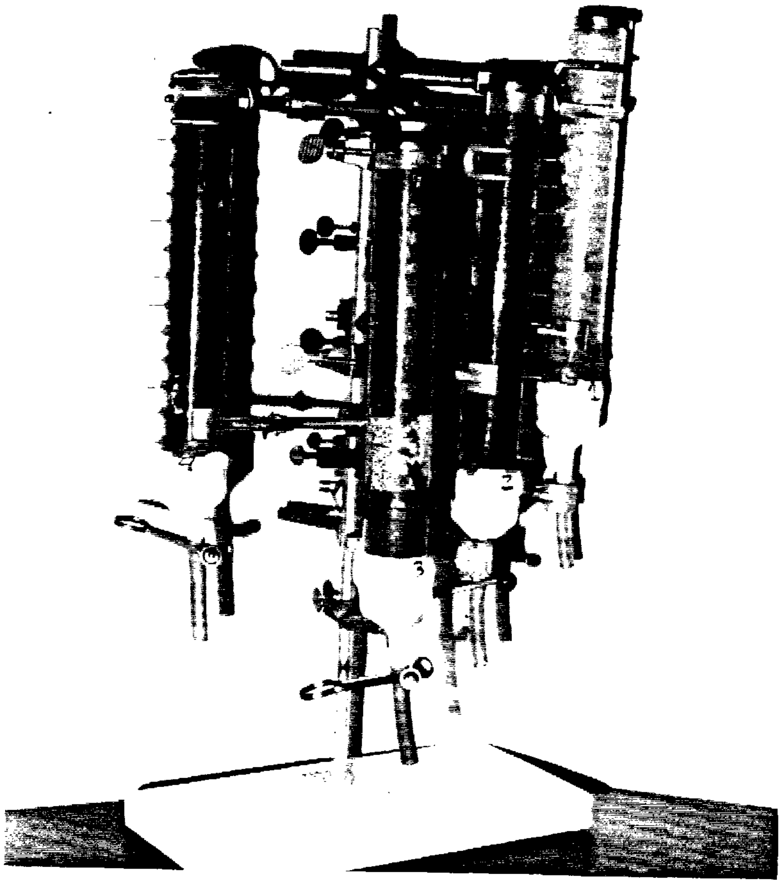


Figure 18 Views of laboratory test columns

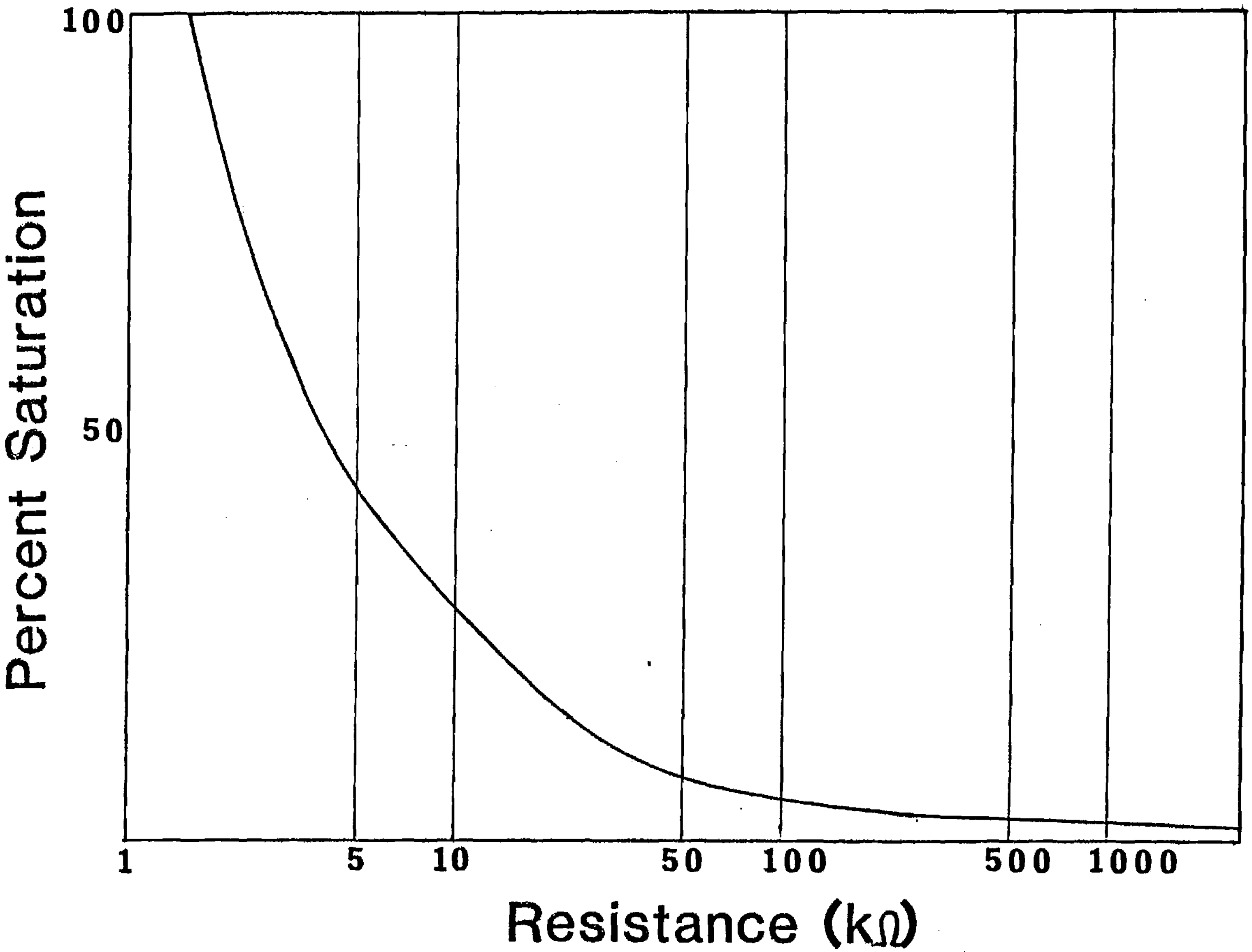


Figure 19 Electrode calibration - GT Sand

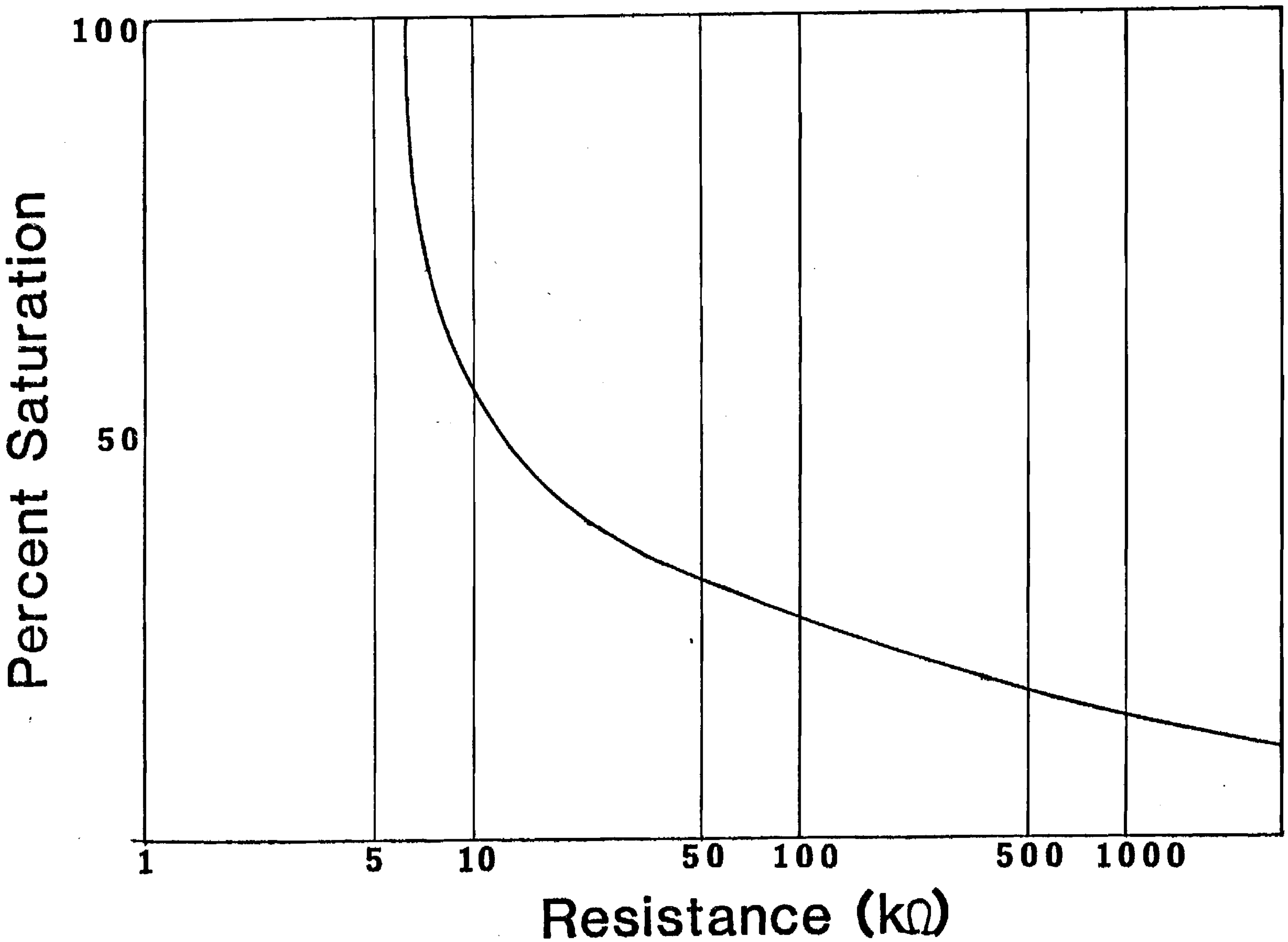


Figure 20 Electrode calibration - SRP # 1 soil

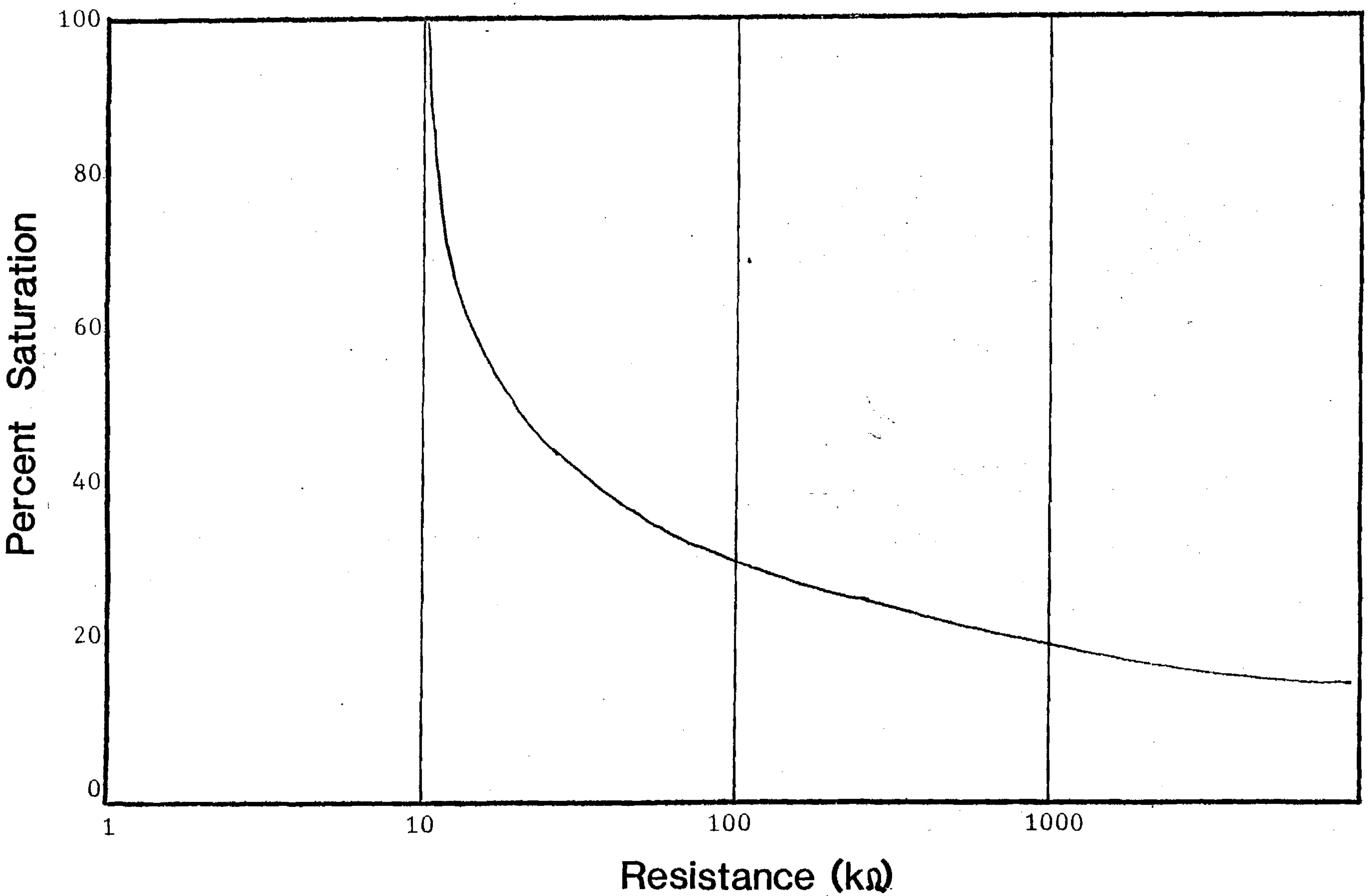


Figure 21 Electrode calibration - SRP # 2 soil

TABLE 6 - RESIDUAL WATER CONTENT FOR SIZED SAND SAMPLES

MESH SIZE	RESIDUAL WATER CONTENT (%)
14-16	0.05
16-20	0.16
25-30	0.18
30-55	0.25
40-50	0.33
50-60	0.61

TABLE 7 - RESIDUAL WATER CONTENT

SOIL TYPE	RESIDUAL WATER CONTENT
Rollo Sand	0.89%
G. T. Sand	1.59
SRP #1	10.51
SRP #2	17.37

One of the consequences of the capillarity effect, also, is the retention of moisture due to surface tension at any major interface. This applies particularly whenever a dense soil layer lies above a cavity, such as a waste volume or a gravel bed. If the interface is sloped, this effect can lead to substantial lateral waste movement. Table 8 records measurements of the wet layers at the open bottom ends of the columns. For the SRP soils this retained wet layer was substantial and even after 30 days there was some continued water loss.

Similar observations have been carried out on the test bed for Rollo sand, GT sand and FP soil. The observed minimum wet base layers were found to be 15cm high for the GT sand and about 30cm for the FP soil.

TABLE 8 - RESIDUAL WET LAYERS AT OPEN ENDS (30 DAYS)

MATERIAL	3CM COLUMN	1.2 CM COLUMN
Rollo Sand	2cm	2cm
G. T. Sand	8	2
SRP #1	14	2
SRP #2	16	2

TEST BED EXPERIMENTS

Use of the test bed had to be planned carefully, if only because the amount of material needed to fill it represented about two cubic yards or about half a ton of soil material, which had to be carefully screened and prepared. Since the tensiometers proved to be insufficiently responsive to rapid changes, most moisture profiles were obtained with the use of electric conductivity probes, which had to be carefully installed and calibrated. An early problem with a floating electric ground potential was overcome by careful grounding of the measuring unit.

The principal purpose of the test bed experiments has been the collection of data on drainage rates, residual moisture, bed support performance and response to cyclic infiltration. At this time, work on the latter effect is continuing and definite results can be reported at this stage only on certain aspects.

Among the most interesting results are a succession of drainage curves of which Fig. 22 is a representative sample. It shows moisture measurements at three levels, z, in the box, 19, 94 and 144 cm. from the top, following saturation loading, in Rollo sand. Drainage is very rapid in this medium and at the 144 cm. level a distinct knee appears demarking the transition from the gravitational regime to the tension regime. Fig. 23 shows the resolution of that curve into two exponential rates from which the appropriate rate constants can be derived. These constants in turn can be inserted into the flow model to determine the time variation in the water content following a step increase in water inflow.

Another type of observation represents the moisture profile for a given water content in the column. Fig. 24 shows a typical profile observed in the test bed. These results have been correlated with calculations of an unsaturated flow model for a cylindrical system. This program can generate moisture contours that are critically dependent on the relative magnitude of the gravitational and the tension drainage coefficients.

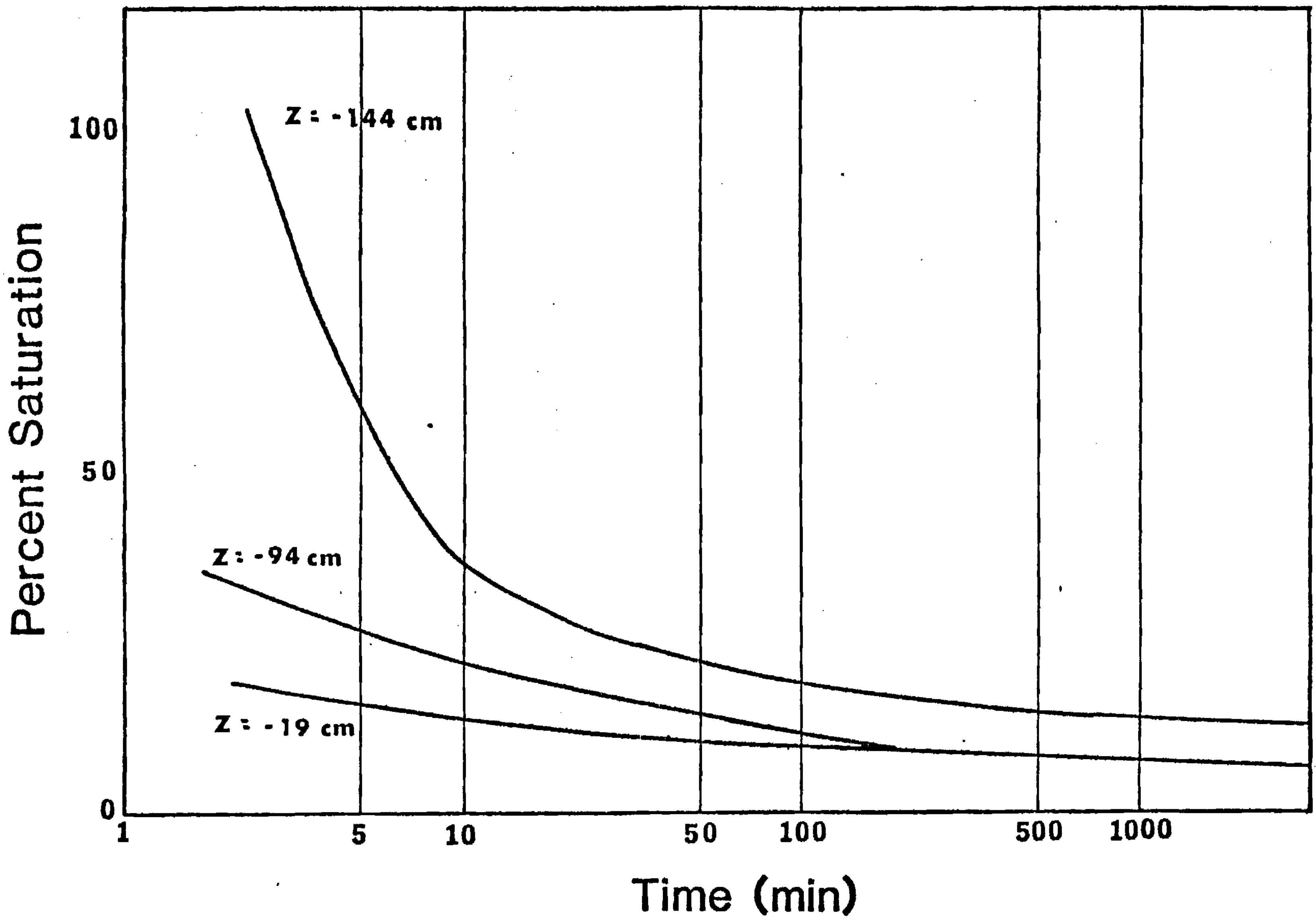


Figure 22 Drainage curves - Rollo Sand

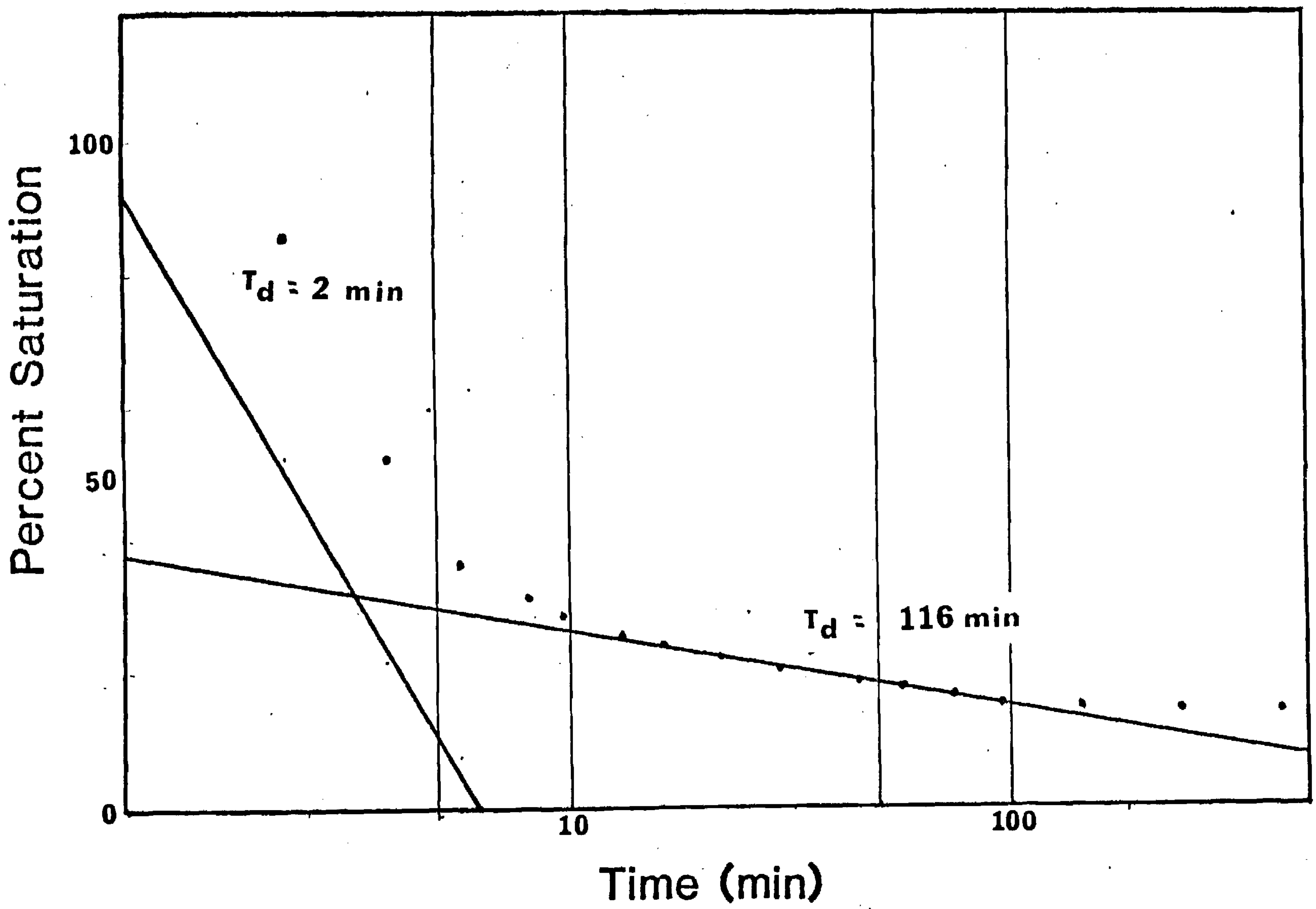


Figure 23 Resolved drainage curve - Rollo Sand

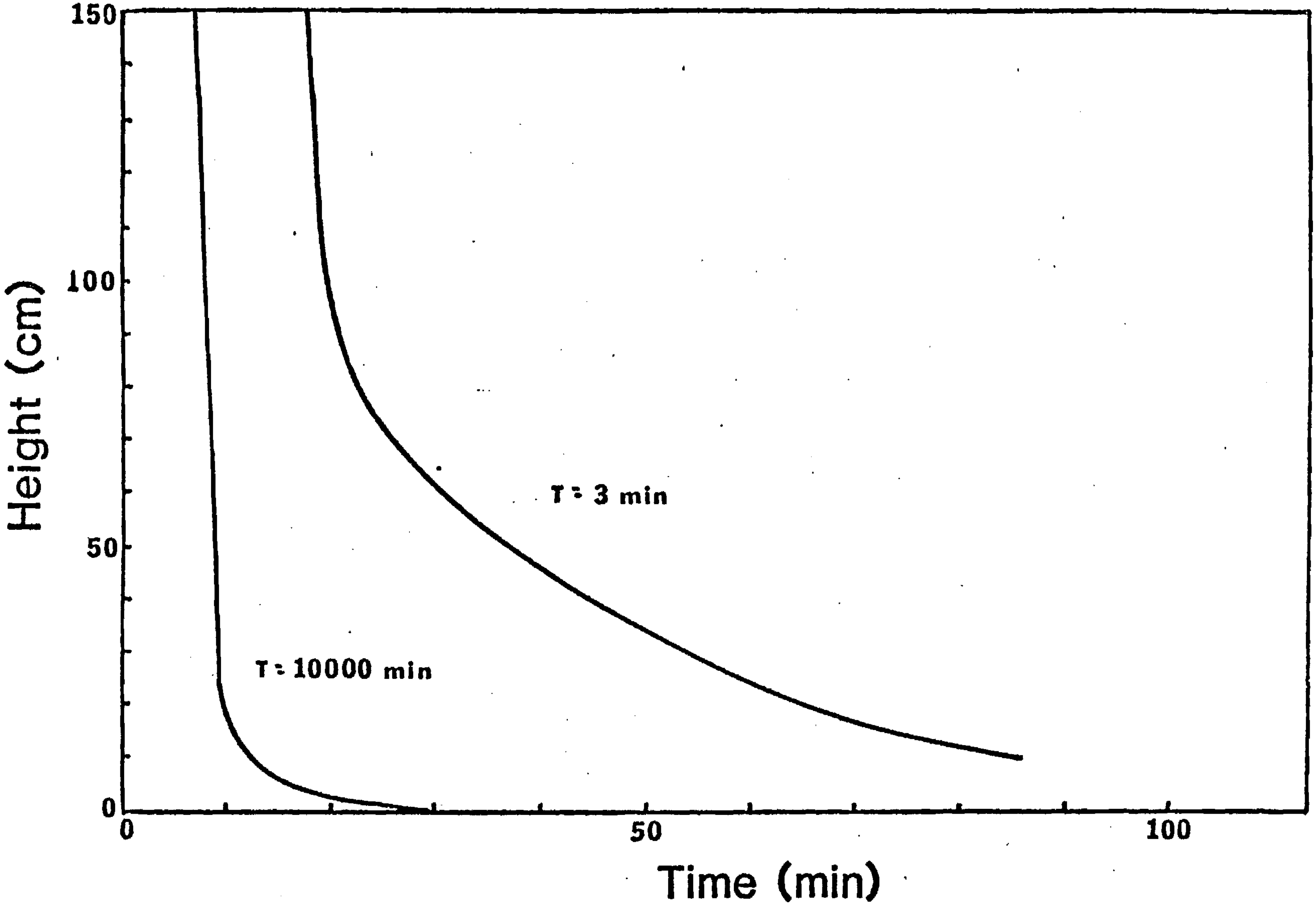


Figure 24 Moisture Profiles - Rollo Sand

Figure 25 shows the moisture profile for GT SAND plotted against the height above the drain. The curve on the right shows the profile at one minute after drainage begins. The middle curve describes the profile after 30 minutes of drainage. The curve on the left shows the moisture profile after 8800 minutes of drainage (about 6 days). The moisture content is seen to be uniform at a height greater than 20 cm above the drain. There is an interface between the soil at residual moisture content (11% of saturation) and the more saturated (75%) soil directly above the drain. Groups of electrodes were placed at 10 cm intervals inside the lysimeter. We cannot determine the exact location of the interface; it lies between 10 cm and 20 cm above the drain. Figure 25 clearly shows that in an unsaturated soil areas of higher saturation can be generated by changes in the soil properties.

Figure 26 is the moisture profile for FP SOIL. The curves compare the moisture profiles at two different times. The curves show the interface between the wet soil and the soil at residual moisture content occurring at a height of between 30 cm and 40 cm. The residual water content of the FP SOIL is estimated to be approximately 30 percent of saturation.

Figure 27 shows the drainage curves for GT SAND at different heights above the drain. The lower curve describes the percent saturation as a function of time for the top of the soil column, 50 cm above the drain and 10 cm below the soil surface. This curve illustrates the initial rapid drainage of the soil followed by a slower decline to the residual moisture content. The upper curve reveals the moisture content at the bottom of the lysimeter, 10 cm above the drain. The graph shows a long plateau where the moisture content at the bottom is nearly constant while the upper portions of the column are draining. It is thought that the infiltration into this zone from above occurs at the same rate as the drainage into the gravel, thereby keeping the moisture content constant. As the upper region approaches the residual moisture content, the downward flow of water slows and the lower area begins to drain.

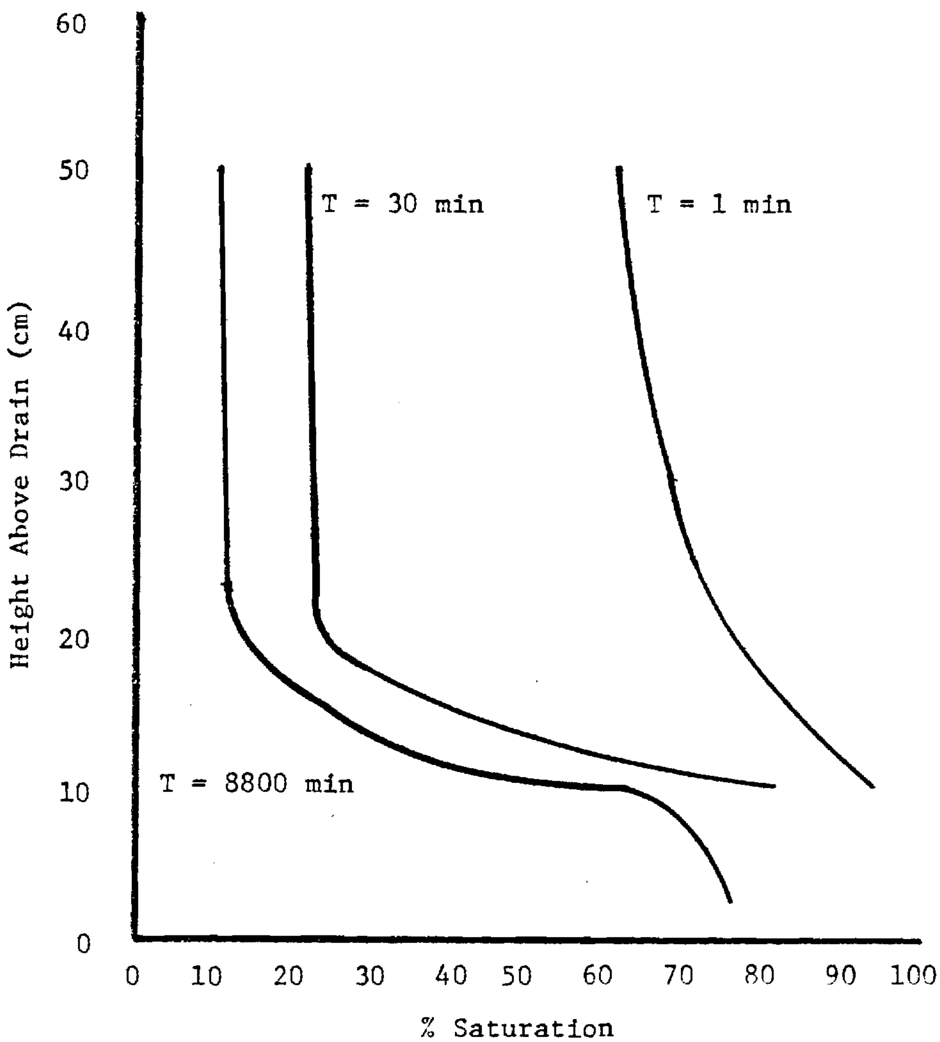


Figure 25 Moisture Profiles for GT Sand at different times

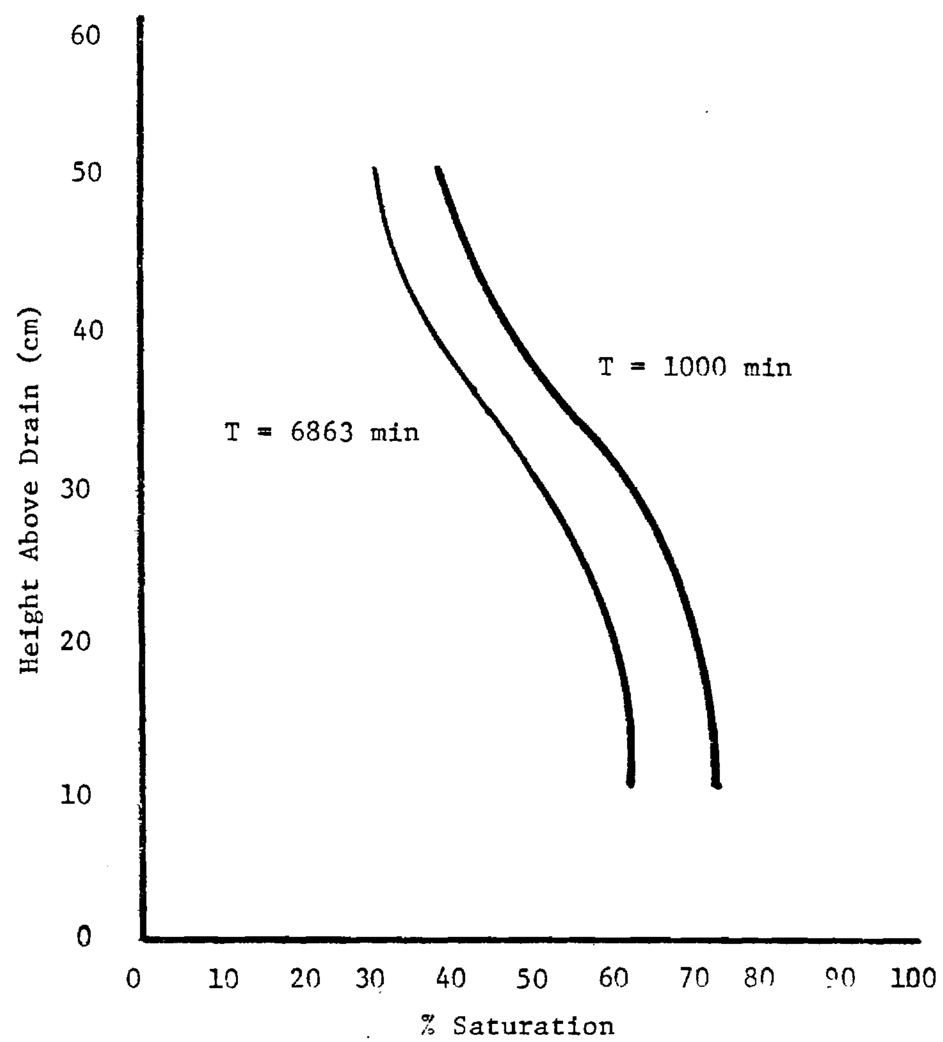


Figure 26 Moisture Profiles for FP Soil at different times

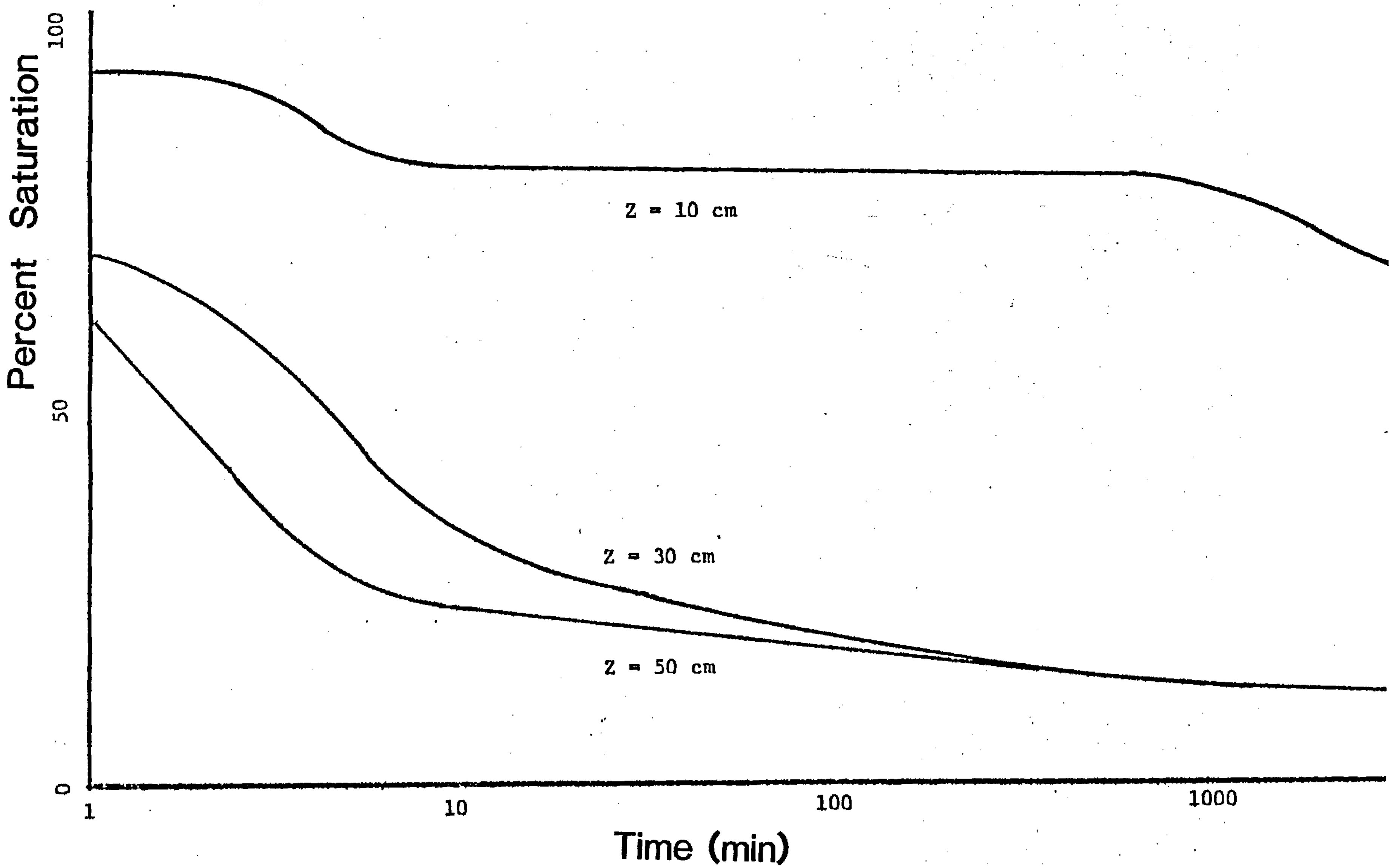


Figure 27 Drainage Curves for GT Sand at different heights

It can be seen from the figure that the drainage from a high percent saturation to a low percent saturation occurs very rapidly in GT SAND. It takes 10 minutes to go from 70 percent of saturation to 30%. The soil returns to its residual moisture content within 1440 minutes (24 hours). If precipitation occurs less than daily, the soil will drain between infiltrations.

Figure 28 shows the drainage curves for FP SOIL at different heights, z, 2, above the drain. The curves are of the same general type as the GT SAND drainage curves. The dotted region between 10 and 150 minutes indicates that the system had not reached equilibrium before the start of the drainage test.

Water was ponded over the soil surface for one hour prior to the start. The Z = 10 cm curve clearly shows the rise from residual moisture content to about 64% of saturation. The residual moisture content of the FP SOIL is about 30% of saturation. This value is reached in approximately 4000 minutes (3 days).

Figure 29 is a comparison of the drainage curves for the three soils. The two sands have similar curves. There is an initial region of rapid drainage followed by a couple of hours of slower drainage. The sands have attained residual moisture content in less than five hours. Rollo Sand and GT SAND have residual moisture contents of 12 and 10 percent of saturation respectively. The FP SOIL, with its significant clay fraction, requires an order of magnitude more time to reach its residual moisture content. The measurements used in Figure 26 were taken 10 cm below the surface.

Figure 30 shows the drainage curves for Rollo Sand and GT Sand resolved into their component parts. The curves are percent of saturation plotted against log time. Both sands show a two-part drainage curve. The initial portion is presumably the gravity drainage of the larger pores and is significant for the first 10 minutes. The second component continues to drain for several hours until residual moisture content is reached. Rollo

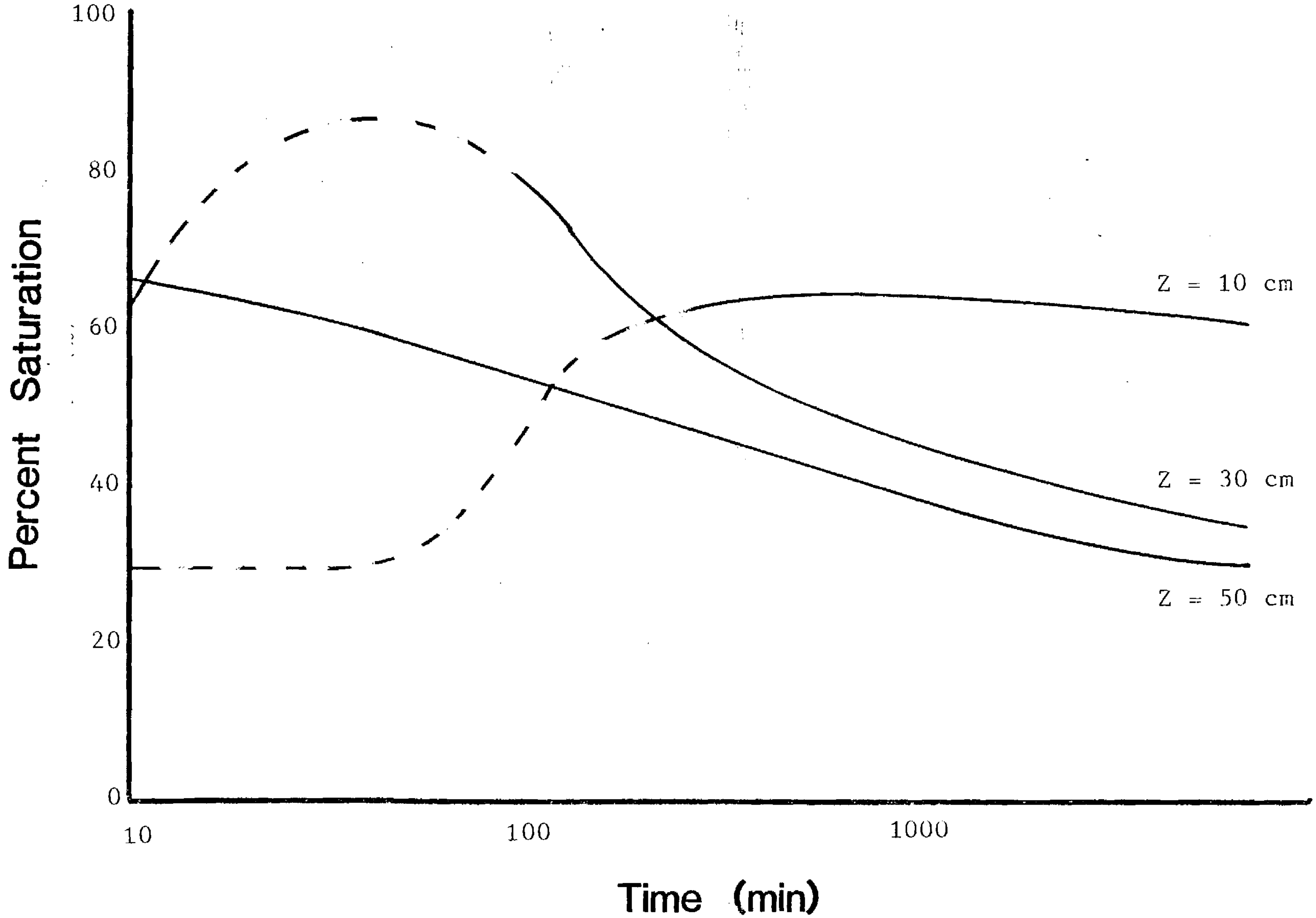


Figure 28 Drainage curves for FP Soil at different elevations in the test bed

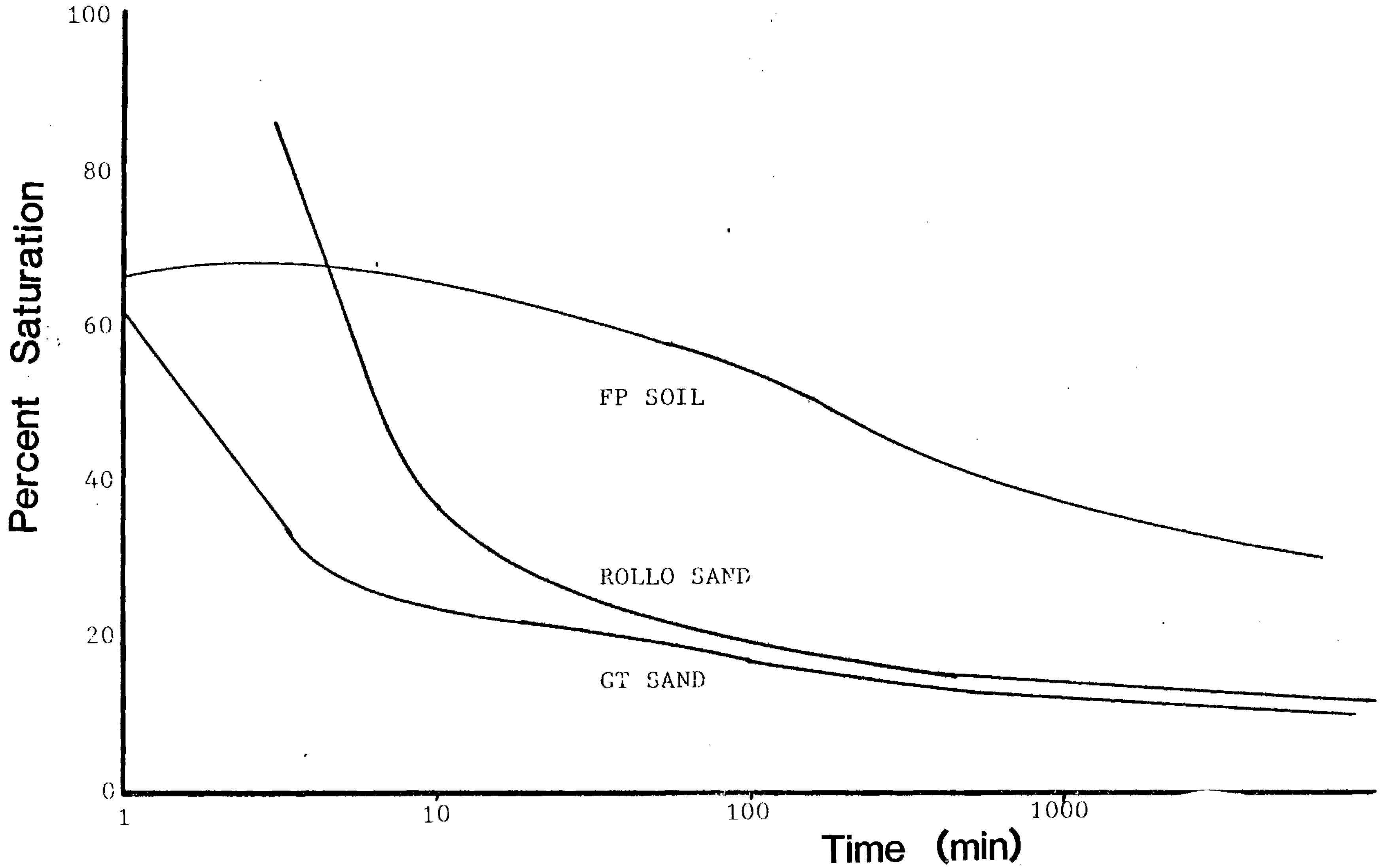


Figure 29 Drainage Curves for three soil types

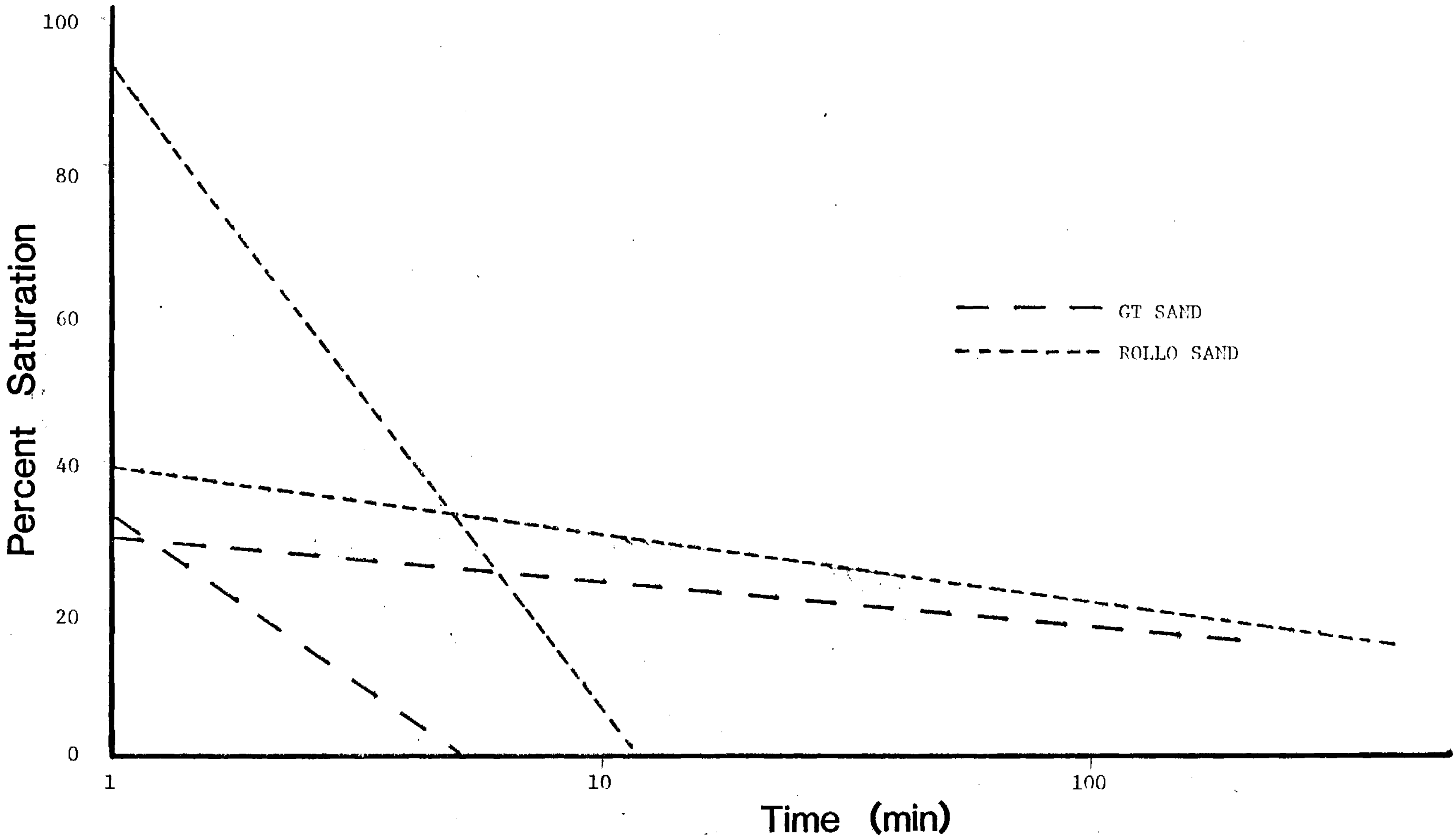


Figure 30 Resolved Drainage Curves for two sands

Sand is shown to drain faster, which is to be expected, due to its large, uniform-sized particles. It is interesting to note that the time of drainage is a function of the percent saturation. The drainage equation can be expressed as:

$$t = C \quad e^{-(k \cdot s)}$$

where t is the drainage time, C is an empirical constant, k is the drainage constant and s is the percent saturation.

Rollo Sand was found to have drainage constants of 0.247 s^{-1} and 0.0266 s^{-1} for the rapid and slow drainage respectively. GT Sand had k's of 0.384 s^{-1}. The initial drainage rates are only significant in the first five to ten minutes. It must be remembered that these values are calculated for the top 10 cm of the soil column. The curves become more complex with depth due to the variable infiltration of moisture from above.

A drainage curve resolution was not done for the FP Soil. The soil had not achieved its equilibrium conditions due to a insufficient initial infiltration time. The experiment is being repeated using a much longer infiltration time.

Calibration of the electrodes was done in the field by taking a soil sample from between each electrode pair. The water content was determined gravimetrically. The bulk density and porosity were also determined under field conditions.

An important feature of a well-drained bed is the retained moisture at the bottom of the column. In the test bed, the sand layers were supported by a mesh screen that was placed on top of the coarse gravel bed which provided the drainage path. In sand, ordinarily, little moisture should be retained due to surface tension effects at the lower surface. However, it was found that the wire mesh supported a film of water of sufficient strength to maintain significant moisture in the sandbed up to a height of about 14 cm. Proper choice of the supporting material is obviously important to minimize this effect, while yet retaining the bed material sufficiently to avoid clogging of the gravel layer. In practice it is felt that a graded gravel layer can supply enough support for the soil and may be preferable to a screen or open-mesh liner material.

Since the usefulness of the drainage layer could be impaired by silting over a long period, qualitative observations were maintained on silt infiltration into the gravel bed. It was found that a little fine silt material was washed into the gravel in the early stages of the test, but later, with the readily mobile material removed from the bottom soil layer, no further silt movement seemed to occur.

WASTE LEACHING UNDER UNSATURATED CONDITIONS

One of the principal objectives of this work is the reduction in the source term from water attack on the waste material by reduction of the quantity of water in contact with the waste and of the time available for transfer processes. For vitrified waste, Pescatore and Machiels (23) have argued that for slow flow rates the diffusion rate of waste ions to the surface layer becomes the rate-determining step. Most waste depository models assume that water flow is continuous, saturated and that the leach rate is proportional to flow rate at a constant solubility. Under unsaturated flow conditions or cyclic flow conditions, it is not at all clear if leaching occurs in a constant fashion and whether it is necessarily proportional to volumetric flow rate. Test work has been conducted with simulated waste to study these processes, but the results have been inconclusive so far, partly because of slow leaching rates and partly because of the need to employ equilibrated water for reasonable simulation, whose composition is, to some extent, affected by the nature of the simulated waste itself. Similar considerations affect the leachability and migration rates of other waste trench simulations, such as the SRP lysimeter tests (15), where flow also is unsaturated much of the time.

The test work conducted in the laboratory has been of two types, recirculating water through simulated waste material and once-through flow tests. The simulated waste consisted on ion exchange resins labeled with Cs-137 or Tc-99m. This material was chosen, because it was felt that other waste forms either would be too insoluble to result in statistically valid desorption or would be too inhomogeneous for comparison. The recirculated tests suffered from constant change in pH due to the effect of the waste resin and those tests were not pursued. Once-through flow tests with equilibrated water were more controllable, but have resulted in too low a level of desorption to yield reliable results. For this reason no experimental results on this aspect of the project are reported here in detail. These tests are continuing and it is hoped to place them on a more productive basis.

In the meantime, for calculational purposes it is assumed that the leach rate is proportional to the time-integrated volumetric flow. That is a problematic assumption, because of the diffusion rate and concentration-gradient dependence of the leach process which makes it improbable that the leach source term is proportional to water volume under pulsed conditions. However, for the moment that assumption seems the best available.

COMPUTER SIMULATION

To evaluate the effects of unsaturated flow under time-dependent conditions, a one-dimensional computer program has been developed. This program can describe pulse flow conditions in the test bed and the movement of the moisture profile. Details of the program are presented in Appendix A.

The results depend, of course, on the relative magnitude of the pressure head (gravitational force) and the suction head (capillarity). Figures 31 and 32 illustrates two cases where their relative magnitudes vary.

The general features of computer model for this facility are shown in Figure 33. On the left are the physical processes involved, on the right the various rate processes that determine waste migration from the source.

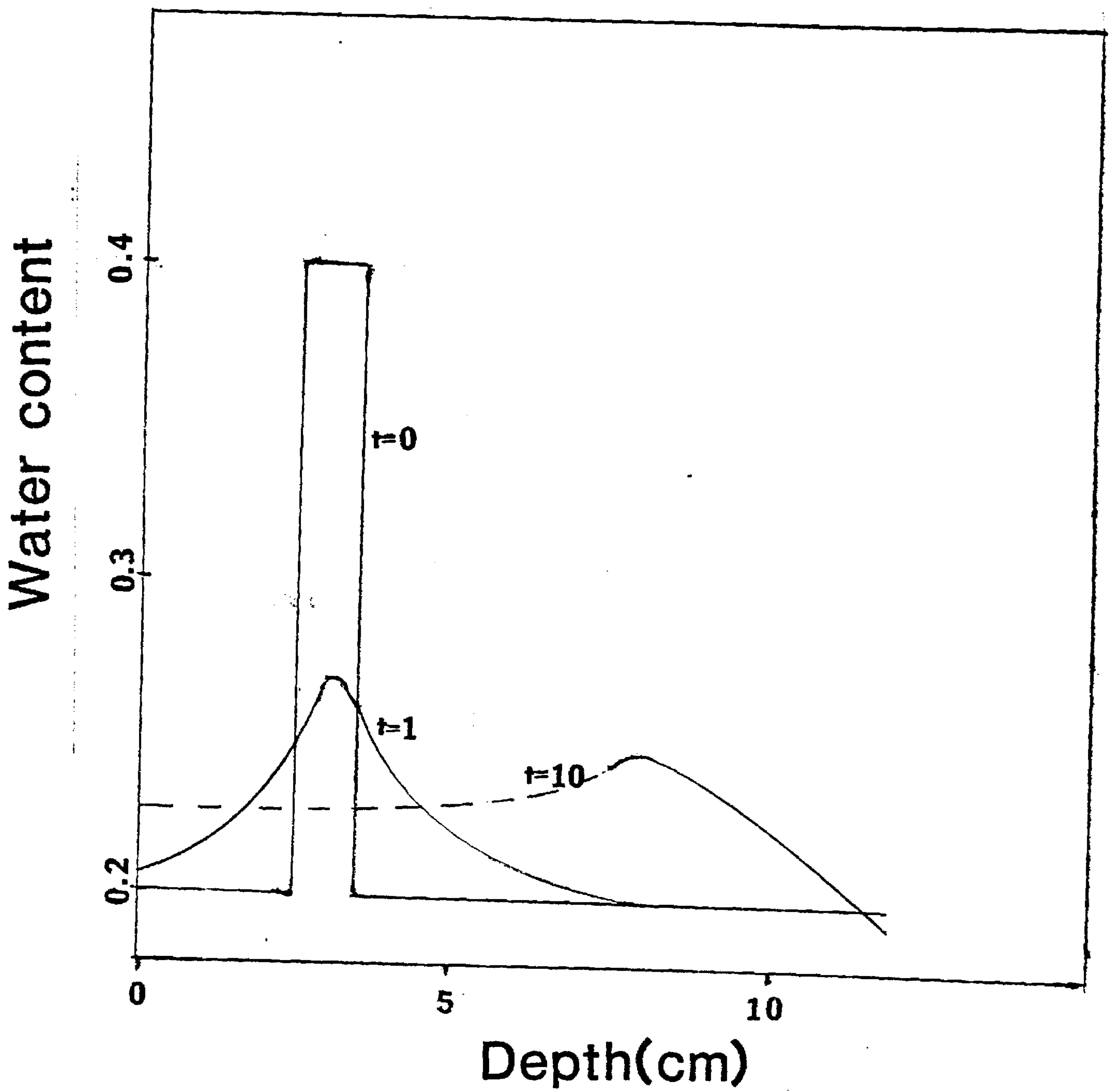


Figure 31 Calculated Moisture Profiles - Comparable forces

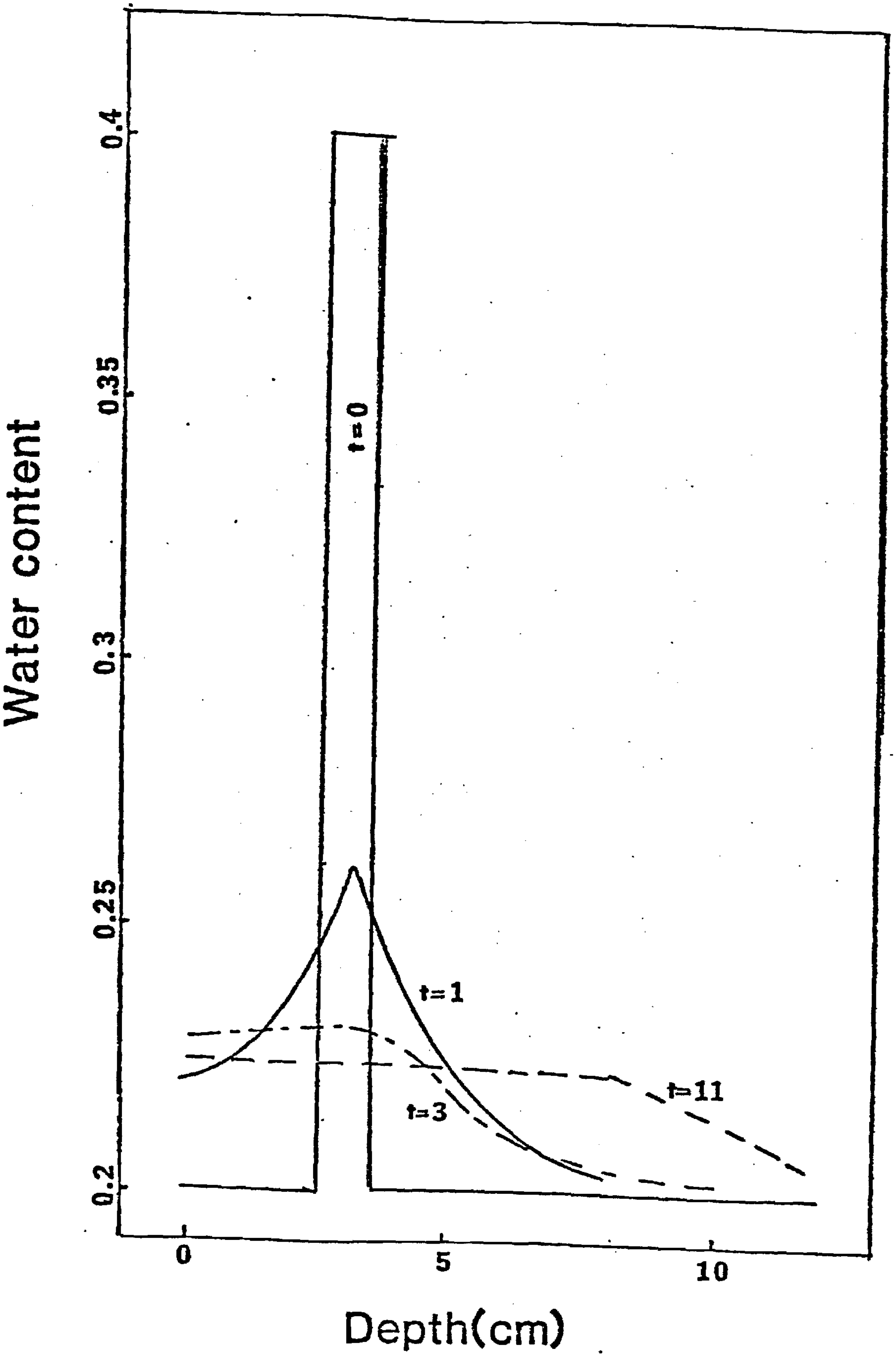


Figure 32 Calculated Moisture Profiles - Suction dominant

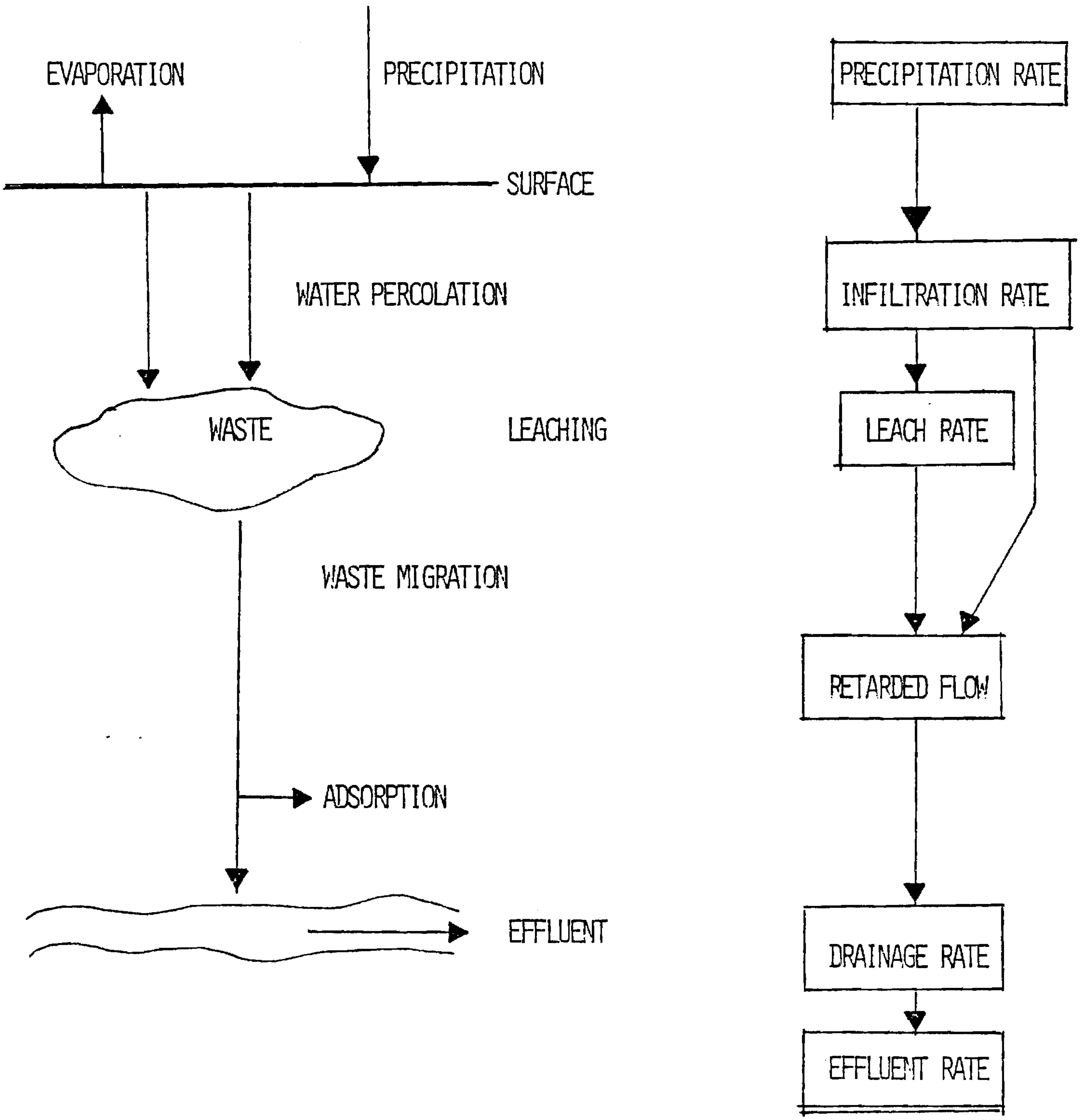


Figure 33 Diagram of Migration Model

Details of the model development go beyond the scope of this report and will be available shortly in extended form (de Sousa, Ph.D Thesis, 1985). The program description is attached in Appendix A - C. The model is based on a finite element technique which was used to solve the one-dimensional unsaturated flow and transport equations. Boundary conditions include provision for a Neumann variable flux condition, so as to represent a seepage boundary, as well as a Dirichlet constant boundary condition.

In order to use the water flow and transport model to simulate a shallow land burial site performance, it is necessary to determine how well the model can simulate the unsaturated regime present in the soils. Since the transport model uses the results obtained with the flow model, the latter was the first one to be checked.

Flow model

The first simulation done to check the accuracy of the water flow model corresponded to the situation in which an homogeneous saturated column of soil was submitted to a constant infiltration equal to the saturated hydraulic conductivity of the soil; the boundary condition at the bottom of the column corresponded to a free draining profile. In this situation the column should remain saturated, and the pressure head should not change with time, since the infiltration and the drainage rates are equal; the results obtained, given in Table 9, showed that the model was simulating that situation correctly. This simulation was useful to the extent that it showed the logic of the model was correct and the matrices were being well assembled and solved.

The ability of the model to reproduce unsaturated flow was checked by simulating the situation presented by Van Genuchten (28) based on the experiments done by Warrick (29). This experiment was chosen because it represents one of the most difficult cases to simulate, which is when a dry soil is subjected to a large infiltration rate.

The experiment consisted of an homogeneous soil column, 125 cm long, which was subjected to the following conditions:

TABLE 9 - FLOW MODEL VERIFICATION

TIME= .050 NL= 1 NT= 1

NNODE	COORDINATE	PRESSURE HEAD
1	.000	-34.460
2	1.000	-34.460
3	2.000	-34.460
4	3.000	-34.460
5	4.000	-34.460
6	5.000	-34.460
7	6.000	-34.460
8	7.000	-34.460
9	8.000	-34.460
10	9.000	-34.460
11	10.000	-34.460
12	11.000	-34.460
13	12.000	-34.460
14	13.000	-34.460

TIME= .125 NL= 1 NT= 2

NNODE	COORDINATE	PRESSURE HEAD
1	.000	-34.460
2	1.000	-34.460
3	2.000	-34.460
4	3.000	-34.460
5	4.000	-34.460
6	5.000	-34.460
7	6.000	-34.460
8	7.000	-34.460
9	8.000	-34.460
10	9.000	-34.460
11	10.000	-34.460
12	11.000	-34.460
13	12.000	-34.460
14	13.000	-34.460

TIME= .225 NL= 1 NT= 3

NNODE	COORDINATE	PRESSURE HEAD
1	.000	-34.460
2	1.000	-34.460
3	2.000	-34.460
4	3.000	-34.460
5	4.000	-34.460
6	5.000	-34.460
7	6.000	-34.460
8	7.000	-34.460
9	8.000	-34.460
10	9.000	-34.460
11	10.000	-34.460
12	11.000	-34.460
13	12.000	-34.460
14	13.000	-34.460

Initial Condition:

$$\theta(x,o) = \begin{cases} 0.15 + 0.0008333 & 0<x\leq 60 \\ 0.20 & 60<x<125 \end{cases} \quad (1)$$

Boundary Conditions:

$$h(\theta,t) = -14.495 \quad (2)$$

$$h(125.t) = -159.19 \quad (3)$$

The water content - hydraulic conductivity and the water content - pressure head relations are given by:

$$0(h)= \begin{cases} 0.6829-0.09524 \ \ln|h| & h\leq -29.484 \\ 0.4531-0.02732 \ \ln|h| & -29.484 < h\leq -14.495 \end{cases} \quad (4)$$

$$k(h)= \begin{cases} 19.34x10^5 \ |h|^{-3.4095} & h\leq -29.484 \\ 516.8 \ |h|^{-0.97814} & -29.484 < h\leq -14.495 \end{cases} \quad (5)$$

The flow model is written in terms of pressure head and so the initial pressure head distribution is given by substituting eq.1 in eq.4; the boundary condition at the surface (eq. 2) implies that the soil is maintained saturated at the top of the column at all times.

The results obtained by using linear finite elements (LFE) and mass lumped linear finite elements (MLFE) are shown in Figure 34, where they are compared to the numerical solution obtained by Van Genuchten (28). It is seen that in both cases a reasonable simulation is obtained; more accurate results can be obtained if the spatial and time intervals are decreased at the expense of a longer computational time. The LFE simulation presented some oscillations at the early stages, that decreased as the time increased. These oscillations can be minimized by again decreasing the spatial and time increments. Under those conditions the flow model generates accurate results when used to simulate unsaturated water flow.

At the time of writing the transport model was being checked, and it was established, that for the same situations used for the flow model, it can be used to simulate the movement of radionuclides through unsaturated soils.

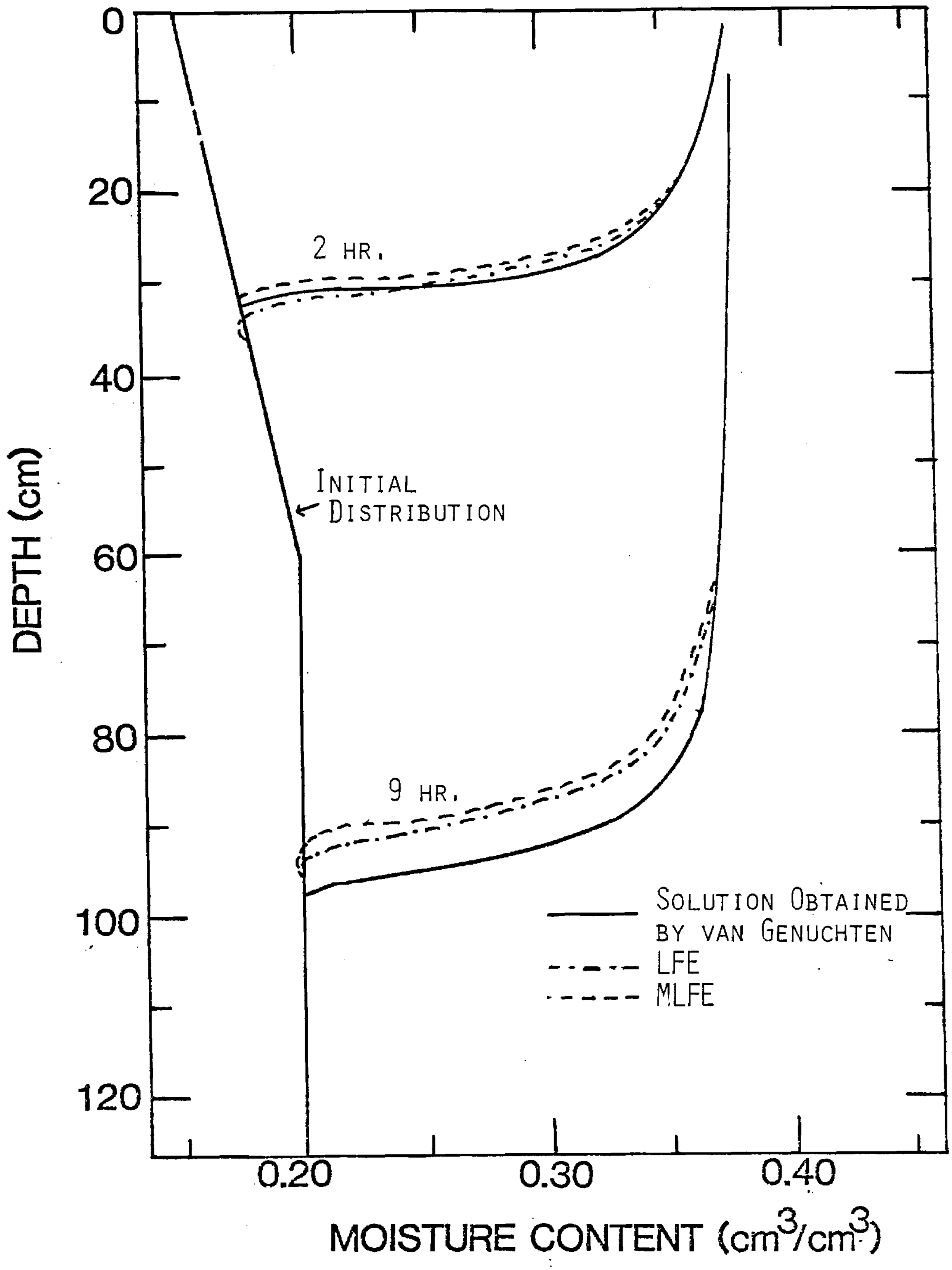


FIGURE 34 VERIFICATION OF FLOW MODEL

TRENCH FACILITY DESIGN

The work described above has provided some guides for the design of a facility that is specifically intended to minimize waste leaching by facilitating drainage through the backfill, thus preventing any standing water in the waste volume regardless of the condition of the cap. Since it has been shown that soils with a high clay content retain a substantial amount of moisture at all times, it is evident that a fairly permeable sandy loam would be preferred for the backfill material.

As Table 8 has shown, even for fairly sandy soil there will be a wet layer of up to 12cm above any gravel base; hence waste emplacement should be on top of a soil layer at least a foot thick. This will also facilitate waste placement and protect the gravel layer against the action of tracked vehicles in the trench.

Figure 35 is a generalized diagram of the trench design envisaged. (A mesh separator between backfill and gravel bed was considered , but present experience indicates that it is probably unnecessary). The main feature of importance is the gravel bed, which is common to most waste trenches, but assumes a central role in the present design. Given a reasonably permeable backfill soil, it is assumed that following a rainfall most of the infiltrated water will percolate rapidly through the backfill to reach the gravel bed, which must have enough capacity to store this water over a long enough period to permit slow, orderly seepage into the ground without backing up. The French drain bed shown would be needed only, if the surrounding soil is so impermeable that backup is still possible or if diversion for seepage to a more desirable, high-exchange capacity, soil is aimed for.

Calculation of Gravel Reservoir Requirements

The quantity of water that must be accommodated in a near-surface burial site is dependent on three major factors. These are the amount of precipitation, the rate of infiltration of water into the soil, and the rate of movement of the water within the soil. The latter two factors are interrelated, as the limiting factor may be either the rate of passage

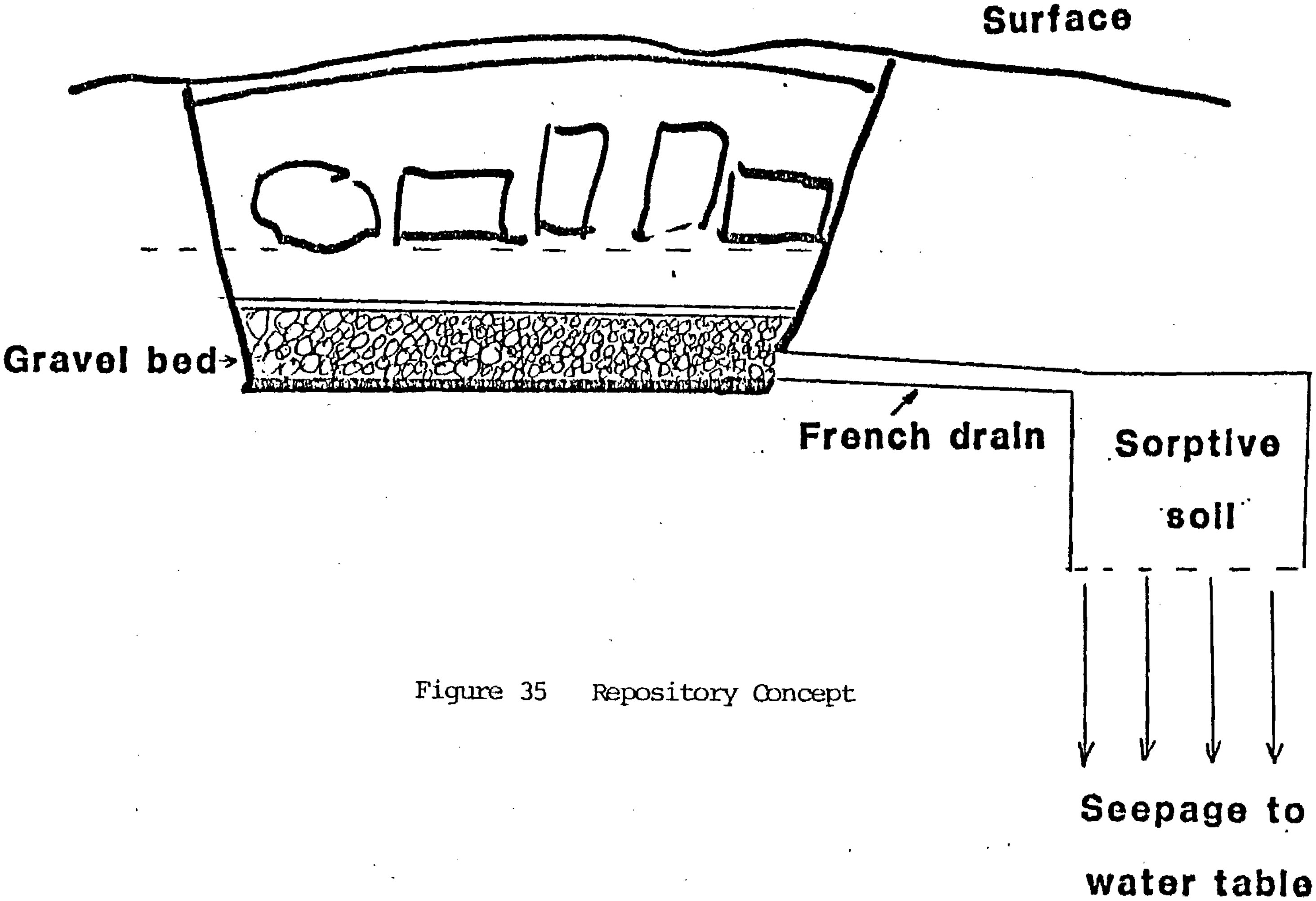


Figure 35 Repository Concept

through the air-soil interface or the rate at which water percolates away from the interface, leaving room for additional water to enter the soil.

Considering the width of a typical disposal trench and the fact that even compacted backfill is likely to be more permeable than most undisturbed soils, seepage from the trench walls may be considered insignificant compared with direct vertical movement. For very impermeable caps lateral flow around the cap edges may have to be considered, but this infiltration component would be otherwise indistinguishable from other infiltrated water as far as moisture retention and waste leaching are concerned. Any flow channeled along the trench wall is unlikely to interact with the waste and will only fractionally increase the reservoir capacity requirements.

The maximum rate at which water can enter the soil under given conditions is called the infiltration capacity. The actual infiltration rate equals the infiltration capacity only when the intensity of rainfall equals or exceeds the infiltration capacity. The infiltration capacity is at its maximum when the soil is dry, but decreases rapidly at the beginning of a storm and approaches a low, constant rate as the soil becomes saturated. The permeability of the subsoil becomes the ultimate limiting factor.

Soil type, moisture content, organic matter, vegetative cover, and other factors affect infiltration, but a decrease in rate with time is generally observed. This is shown in Fig. 36, where infiltration rate is plotted against time for two typical soil types (25). The difference between plots for dry (initial) conditions and wet condition demonstrates the large influence of existing moisture content of the soil.

For purposes of calculation, it was assumed that the soil of the burial site is similar to Houston black loam in its infiltration capacity. The scenario for the maximum volume of water would be to commence with dry soil. This allows a high rate of infiltration at the very start, but within 30 minutes this has fallen by approximately an order of magnitude with additional significant rate decrease in the subsequent hour. It is estimated that during the first three hours of rainfall of intensity

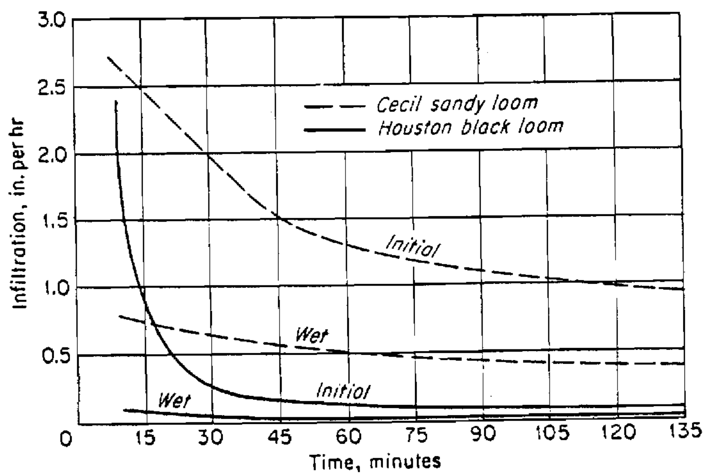


Figure 36 Comparative infiltration rates during initial and wet runs (after Ref. 25)

sufficient to keep the soil surface covered, the total infiltration will be one inch. After three hours the rate for any continuing rainfall period is 0.05 in/hr, (0.125 cm/hr), the equilibrium flow rate.

The total inflow of water into the burial site during a given episode, therefore, depends on the length of time that the surface of the ground is wet enough to supply 0.05 in. of water per hour. No records of periods of continuous rainfall in the southeast have been located, and the Atlanta Weather Bureau is of the opinion that no such records have been kept. In reviewing the rainfall records for the Atlanta area, it was found that maxima are tabulated for one, two, and seven-day periods. It is considered unlikely that rain would occur continuously for more than a few days, based on seven-day records of 9 inches (10 year return), 10 inches (25 year return) and 12 inches (100 year return). It is therefore concluded that the maximum quantity of rainfall will be 9.25 inches, (23cm) obtained from the sum of one inch in three hours plus 0.05 in/hr. for 165 additional hours. It is further noted that the return period for this maximum is greater than 10 years, and is more likely to exceed 25 years.

This is based on the assumption of a week during which the rain falls steadily and virtually no surface run-off occurs, a set of circumstances that clearly would not occur very often. The quantity of infiltrated water would also be reduced by evapotranspiration, estimated at 0.25 inch per day. On this basis, the total quantity of water to be considered is reduced to 7.5 inches (18.75cm).

The passage of water from the surface of the ground to the junction with the water table is envisioned as follows: After penetration of the air-ground interface, the infiltrating fraction of the water proceeds downward at a slow rate determined by the characteristics of the compacted fill soil. It then enters the zone where waste materials have been placed. It is highly unlikely that the waste containers could ever be placed in a very tight configuration and cracks, crevices, and void spaces would be plentiful. Also, any back-filled soil that subsides into the main volume of waste is not likely to be very well compacted, so the entire waste zone will be conducive to the rapid percolation of water.

The rate of movement of water into the underlying and surrounding undisturbed soil will be lower than the rate of movement through the waste, so a storage volume beneath the waste will be required to prevent water from standing in the waste zone. It is estimated that infiltration will proceed twice as fast through the backfill as through the undisturbed lower strata, so for a steady input of 7.5 inches of water in a week, an accumulation of 2.25 inches (5.6cm) of water can be calculated.

The storage volume under the waste can best be provided by a layer of a highly porous nature. A granular material such as small gravel or coarse sand would be appropriate, but the interstices must be small enough to prevent significant invasion of fines with subsequent clogging. AASHTO number 89 stone would be an appropriate choice, as it would provide a very permeable zone and would not require the placement of a number of layers of different sized media. If compacted to a reasonable density, the void volume of 89 stone is in the 20-25% range. It would therefore require a theoretical depth of 11.25 inches to hold 2.25 inches of water. Such precision is not warranted and specification of one foot (30cm) of this material will assure a very conservative volume.

Placement of a foot of small gravel, such as 89 stone, under the disposal trenches is a reasonable measure which should provide long-term assurance that the layer would retain its capacity even with a limited amount of siltation from the lower reaches of the backfill.

It may occur that site considerations will make it desirable to increase the size of the drainage area or to move it completely from under the burial area. This can be accomplished by drain lines leading from the layer of emplaced gravel to another drain field. Clay pipes are satisfactory for this type of service as they are resistant to chemical deterioration, can be installed without any particular difficulty, and should remain trouble-free for a very long period of time. They are susceptible to breakage, however, and could be destroyed by the heavy equipment used to place and compact the waste materials.

While the installation of drain lines entirely across the bottom of the excavation within the gravel layer would provide very rapid discharge from the gravel, this is not mandatory. If the lines extend into the gravel a limited distance, the desired result will be obtained because of the very high rate of tranmission of water by the gravel layer. From the practical view, it could be advisable to delay installation of the drain tile and its limited adjacent gravel area until the balance of the trench was already filled and compacted.

More than one line should be installed so that the system could operate in a fairly normal manner, even if some of the pipes were broken or became clogged with silt or roots. In the areas where exfiltration is intended, the pipes would be laid with open joints in ditches with a layer of gravel. Tight pipe joints would be used in any zone where dispersion of the water was not wanted.

The area of the extended drain field will be governed by the relative permeability of the subsoil in relation to the permeability of the soil cap covering the waste. In the situation of a remote drain field of the same area as that of the burial excavation, if the soil permeability is less than half of that of the cap, the potential maximum accumulation of water will be more than the 2.25 inches calculated above. This increase can be offset by a deeper gravel layer or a larger drain field, but the volume of the drain lines themselves may be large enough to be significant. In any event, the effect of pipe volume should be considered.

A downward slope of the drain lines is needed, but it does not have to be a very large slope. The usual design of a drain field involves parallel pipe lines fed by a header, but the long-term reliability of the system can be increased by the addition of extra connections at intervals between the parallel lines. This will provide a grid so that in the event of a stoppage, flow to most points can be provided from the other direction.

No unusual requirements are placed on the subsequent seepage path to the aquifer. A fairly clayey soil and a reasonable distance to the water table are desirable and the orientation of the drain field can be chosen to optimize the final water flow direction in this respect. Since the source term is expected to be lower, the retention capacity of the seepage path also need not be as high as for the saturated flow condition and a wider area can be drawn into service, subject mainly to cost and land use limitations.

CONCLUSIONS

The work described in this report addresses three issues: a) What are realistic flow conditions in a near-surface disposal trench?; b) How can the water content of the waste layers and the surrounding soil be minimized to permit source reduction?; and c) What modifications in conventional trench design are required to meet this objective?

It has been shown, both by laboratory column tests and with a larger test bed, that sandy or relatively permeable soils will drain fairly rapidly to a low residual moisture level as long as there is a gravel layer below the bed capable of receiving this water. In most parts of the United States rainfall and consequent infiltration into soil, even in the absence of an impermeable cap over the trench, result in a low enough water flow that drainage to unsaturated conditions can occur rapidly in most such cases. In the case of soils with a high clay content, such as the SRP #2 soil, drainage in compacted soil would be much slower, the residual water content may be of the order of 20 - 30% of saturated content, and the standing wet column above the soil-gravel interface may be of the order of a foot (30 cm). In general, such soils should be avoided in designing a drainable trench.

By downgrading the importance of a trench cap, the drained design places fewer limits on trench dimensions, since the gravel layer capacity has to be merely capable of accommodating the infiltrated water flow per unit area. The shaping of trench walls will be governed primarily by slope stability considerations, as in conventional trenches. In most other respects the introduction of the gravel layer at the trench bottom does not change any other trench parameters, other than the recommendation for a buffer soil layer between the gravel layer and the bottom of the waste emplacement. Waste spacing would still be governed primarily by subsidence considerations and ease of backfill. Where the compacted backfill soil is of low permeability , it is recommended to mix some sand into it to improve draining characteristics.

Grading of the backfill would be desirable only near the surface to the extent that a multilayer cap is desired to deflect water infiltration. However, this may be an unnecessary expense as some subsidence may still occur and only a specially constructed, relatively expensive reinforced trench cap would be expected to meet that objective completely over the design life of the facility.

For all but the most impermeable soil types, the extra drain field shown in Fig. 35 would not be needed. Instead, the gravel layer, with its low but freely mobile water layer, will provide a head for slow seepage of water into the underlying ground where, on the way to the water table, any remaining dissolved radionuclides would be subject to soil-sorption retardation effects. Because of the absence of standing water surrounding the waste materials there would be a much lower level of dissolved activity in the water, including probably a lower tritium content.

As expected, the leach tests done under simulated unsaturated flow conditions showed very low leach rates and, though these results cannot be considered conclusive at this stage, it is reasonable to assume that with less average water contact with the waste, the source term will be reduced proportionately. This reduction will then carry through into any calculations of predicted population dose from the facility.

The drained trench approach has been, incorrectly, described as a "controlled release" procedure, which would not be in accordance with 10CFR61 regulations. It would be more appropriate to say that it is a more realistic evaluation of what happens in a burial trench and is a preferable approach to a setting that invites bathtub conditions that would lead to uncontrolled release and a very rapid return of contaminants to the biosphere. The drained-trench approach is expected to reduce waste leaching significantly, though additional work is required to determine just how much. By eliminating standing water in the trench, frost and subsidence effects should be reduced. The backfill material would normally be more permeable than the undisturbed soil, resulting in lower residual moisture levels, but in some locations it may be desirable to mix some sand or sandy loam into the backfill.

The extra cost of providing a foot-deep layer of gravel or 89 stone is not significantly higher than the base preparation currently practiced in preparing disposal trenches. An extensive drain field would entail additional costs compared with current procedures, but would not be needed in most cases; on the other hand, much of this added cost would be recovered by the lesser need for very rigid and elaborate cap designs that are proposed by some at present (26). The principal benefit of this approach lies in the expected reduction in source terms, thus meeting the ALARA criterion.

The work has shown the importance of taking unsaturated flow conditions into account in designing a facility and assessing its impact. Although it is easier and "conservative" to model saturated flow, it is evident that the calculated impacts may be orders of magnitude too high and give an unrealistic impression of the radiological consequences of trench construction (27). It is still important to bury predominantly solid waste, but in a carefully chosen medium proper drainage would be expected to provide better insurance in the long run against excessive leaching and release, than reliance on trench cap performance.

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APPENDIX A

Water Characteristics, Hydraulic Conductivity and Sorption Models

by F. N. Carneiro de Sousa

What makes the unsaturated flow equation difficult to solve is the fact that the pressure head and the hydraulic conductivity are both a function of the water content; these relations can be incorporated in the model in table form or by means of analytical expressions. In this study the available data for each soil type was fitted to three different analytical relations, which were called Brooks and Corey, Haverkamp, and Van Genuchten models.

The solution of the transport equation needs also a relation to represent the sorption process. The model was developed in such a way that any equilibrium sorption model can be used, and the three most used ones are described in this section. Some alterations have to be done if a kinetic sorption model is to be used.

1. - Water characteristics and Hydraulic Conductivity Models

a - Brooks and Corey

Brooks and Corey (1964) suggested the following relation to represent the soil-water characteristics

$$\frac{\theta - \theta_r}{n - \theta_r} = \left(\frac{\psi_e}{\psi}\right)^{\lambda} \qquad (A.1)$$

where θ is the volumetric water content, n is the porosity, θ_r is the residual water content, ψ is the soil suction, ψ_e is the air-entry value, and λ is the pore-size distribution index.

The associated hydraulic conductivity is given by

$$K = K_s \left(\frac{\theta - \theta_r}{n - \theta_r}\right)^{\frac{2 + 3\lambda}{\lambda}} \qquad (A.2)$$

where K is the unsaturated hydraulic conductivity and K_s is the saturated one. This equation was obtained by Brooks and Corey with the use of the Burdine theory (see Van Genuchten model). If the Mualem theory is used the equation becomes

$$K = K_s \left(\frac{\theta - \theta_r}{n - \theta_r}\right)^{\frac{4 + 5\lambda}{\lambda}} \qquad (A.3)$$

This set of equations is one of the most used to describe the hydraulic properties of the soil.

b - Haverkamp

Haverkamp (Haverkamp et al., 1977) proposed the following relation for the soil-water characteristics based on laboratory infiltration experiments:

$$\theta = \frac{\alpha (n - \theta_r)}{\alpha + |h|^\beta} + \theta_r \qquad (A.4)$$

where n is the porosity, θ_r is the residual water content, h is the pressure head, and α and β are empirical constants.

As is discussed by McKeon (McKeon et al., 1983), this relation provides for the proper behavior of the soil-water characteristics, since as h approaches zero, the water content approaches saturation, and as h assumes large negative values, the water content approaches the residual value.

The associated hydraulic conductivity relation is given by

$$K = K_s \left(\frac{A}{A + |h|^\beta} \right) \qquad (A.5)$$

where K_s is the saturated hydraulic conductivity and A and β are empirical constants.

c - Van Genuchten

Van Genuchten (1978) presents a relation for the soil-water characteristics which is a development of the Haverkamp relation; it is given by

$$\theta = (n - \theta_r)\left(\frac{1}{1 + |\alpha h|^\beta}\right)^\lambda + \theta_r \qquad (A.6)$$

where α and β are empirical constants and $\lambda = 1 - 1/\beta$. This equation provides the same limits and smoothness as those obtained with the Haverkamp model.

The hydraulic conductivity/water content relation presented by Van Genuchten (1980) is an integral form of the Childs and Collis-George (1950) equation, which is an attempt to calculate the unsaturated hydraulic conductivity using a pore-size distribution obtained from the soil-water characteristics curve. Several investigators modified the equation, and Mualem (1976) presented a simple analytical model given by

$$K_r(\theta) = \frac{\left\{S_e^\beta \sum_{i=1}^{m} \frac{2(n-i)+1}{\psi_i^2}\right\}}{\left\{\sum_{i=1}^{m} \frac{2(m-i)+1}{\psi_i^2}\right\}} \qquad (A.7)$$

where m represents the total number of intervals into which the water content is divided (water characteristics curve), n is the number of intervals up to a prescribed value of θ, β is a constant related to the pore-size distribution, $S_e = (\theta - \theta_r) / (n - \theta_r)$, and $K_r = K/K_s$. If $\beta = 0$, Collis-George equation is obtained; if $\beta = 4/3$, it becomes Millington and Quirk (1959) equation; if $\beta = 1$ Kunze (Kunze et al., 1968) is obtained. Mualem (1976) presented an alternative formulation given by

$$K_r = (S_e)^{1/2} \left[\int_0^{S_e} \frac{dS_e}{dh} \Big/ \int_0^1 \frac{dS_e}{dh} \right]^2 \tag{A.8}$$

A similar equation is given by Burdine (1958)

$$K_r = S_e^2 \left[\int_0^{S_e} \frac{1}{h^2} dx \Big/ \int_0^1 \frac{1}{h^2} dx \right] \tag{A.9}$$

The equation presented by Van Genuchten (1980) is an integral form of the Millington and Quirk equation, and is given by

$$K = K_s S_e^{1/2} \left[1 - \left(1 - S_e^{1/\lambda} \right)^{\lambda} \right]^2 \tag{A.10}$$

where $S_e = (\theta - \theta_r)/(n - \theta_r)$, and λ and β and α (from eq. A. 6) are empirical constants obtained from the shape of the water characteristics curve. The advantage of this model is the ability to fit data in the near saturation range.

2-Equilibrium Sorption Isotherms

a-Linear Adsorption

The linear adsorption isotherm is the most common relation used to simulate the sorption of radionuclides by the soil particles. It is given by

$$S = K_d\ C \tag{A.11}$$

where S is the amount of solution absorbed by the soil matrix, C is the concentration of solute in the soil solution and K_d is the distribution coefficient. The velocity of the tracer (V_t) is related to the water volocity (V_e) by

$$V_t = V_w/R \tag{A.12}$$

where R is the retardation factor which is given by

$$R=1 + \frac{\rho K_d}{\theta} \tag{A.13}$$

where ρ is the bulk density.

The disadvantage of this relation is that it assumes equilibrium conditions, and it does not describe a maximum quantity of adsorption. On the other hand, its use makes the transport equation linear, facilitating the numerical simulation. A similar relation is presented by Lapidus and Amundson (1952),

$$S = K_1 C + K_2 \qquad \text{(A.14)}$$

where K_1 and K_2 are constants.

b - Freundlich Isotherm

The Freundlich (1926) isotherm is given by

$$S=K C^n \qquad \text{(A.15)}$$

where S is the amount of solute adsorbed per unit weight of soil, C is the equilibrium solute solution concentration, and K and n are constants. If n is equal to zero, it becomes the linear isotherm. The disadvantages are that equilibrium conditions are assumed, it does not specify a maximum quantity of adsorption, and its use makes the transport equation non-linear, which implies in an i terative solution.

c-Langmuir Isotherm

The Langmuir isotherm (1918) was originally developed to describe the adsorption of gas molecules onto the surface of solids; it was after extended to represent the adsorption of aqueous solutes onto solid sorbates. It is given by

$$S = \frac{K\ b\ C}{1 + K C} \tag{A.16}$$

where S is the amount of solute adsorbed for unit mass of solid, C is the equilibrium solute concentration, K is a constant related to the energy of adsorption, and b is the maximum amount which can be adsorbed by the solid. It becomes the linear isotherm as C approaches zero. The disadvantage is that it assumes equilibrium conditions, and the transport equation becomes non-linear when it is used.

Other equilibrium sorption isotherms as well as kinetic sorption models are given by Travier and Etnier (1981).

APPENDIX B

MODEL IMPLEMENTATION

In this appendix a description is given of the one-dimensional unsaturated flow and transport mode. The program consists of a main program and 12 subroutines. The main program is responsible for the organization of the program, basically, it performs the scheme shown in Fig. 37.

Subroutine INPU1 is used to initialize the values of all variables needed for the solution of the water flow equation; it defines the geometry and the initial and boundary conditions of the case under study; it also introduces the physical and chemical properties of the soils. Subroutine INPU2 is used to introduce the values of the variables needed to obtain the solution of the transport equation; it includes the initial and boundary conditions as well as the soil properties that were not already introduced by INPU1.

Subroutine SET performs a coordinate transformation; it changes the global coordinates of the nodes of each element to a local coordinate system, which simplifies the evaluation of the element matrices.

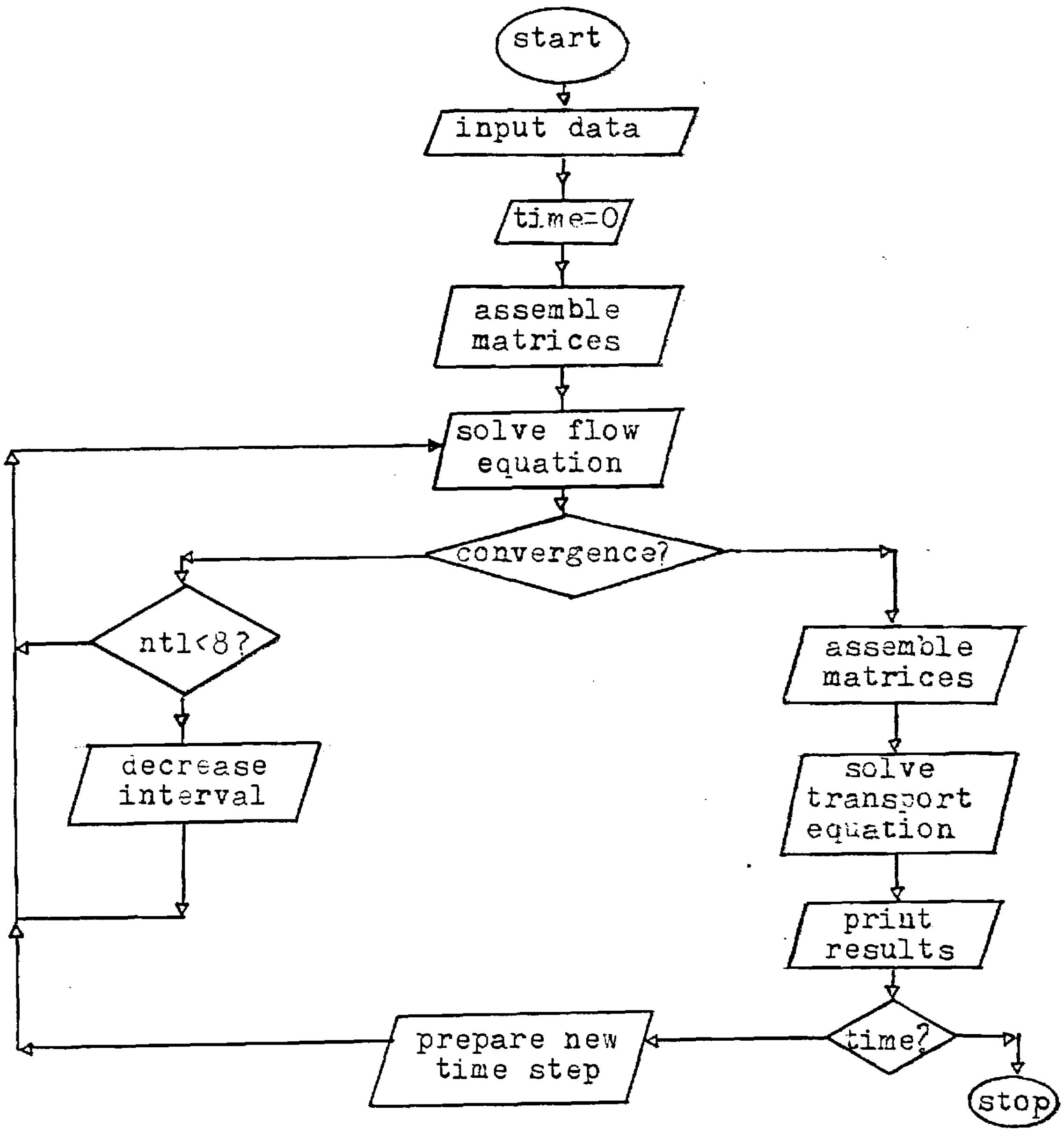

Fig. 37 Model Flow Diagram

Subroutine ELEM generates the local element matrices by calculating each coefficient of the matrices necessary to solve the matrix flow equation. Subroutine ELEM 1 does the same calculations for the transport equation. The soil properties needed for the evaluation of the matrix coefficients are calculated in subroutine HCWC, which is called by subroutine ELEM.

Once the global matrices are assembled, a set of partial differential equations is obtained; these equations are solved by applying a finite difference scheme, and this is done in subroutine CALC1. This subroutine is also responsible for the introduction of the boundary conditions. The output of this subroutine is a system of ordinary equations which is solved by subroutine SOLVE. The method used to solve these equations is the Thomas algorithm, which is a special form of the Gaussian elimination method.

When the solution is obtained for the flow equation, the convergence criteria is checked by subroutine ERROR. If convergence is not attained, the iterative process continues; if convergence is attained, the variables needed for the solution of the transport equation are evaluated by subroutine PROP and the transport equation is then solved. Subroutine OUT presents the values of the hydraulic head, water content, and solute concentration at each time interval.

Table B.1 presents the major variables used in the numerical implementation of the program; Table B2 presents the input cards needed to solve the flow equation, and Table B.3 presents the listing of the actual program.

TABLE B.1 - PROGRAM VARIABLES

AG(30.3)	-	Global matrix
AI(3)	-	Residual Water Content of each soil
AL1	-	Distance between the two last nodes of the soil column.
ALF(3)	-	Compressibility of the soil
BI(3)	-	Value of in eq. A.4 and A.5, and value of in eq. A.1
BUD(3)	-	Bulk density of the soils.
CI(3)	-	Pore-size distribution index.
CL	-	Value of the constant concentration at the last node of the column when a constant boundary condition is used.
CO(20)	-	Variable concentration at the top of the column when a variable boundary condition is used.
CON(30)	-	Concentration at time .
CONI(30)	-	Initial concentration profile.
COO	-	Constant concentration at surface when a constant boundary condition is used.
DEV(30)	-	Value of at each node.
DEVO(30)	-	Value of at each node.
DI(3)	-	Value of A in EQ. A.5
DICO(30)	-	Distribution coefficient of each soil
DIFU(3)	-	Diffusion coefficient of each soil
DISP(3)	-	Dispersivity of each soil.
EI(3)	-	Value of in eq. A.5
ERR1	-	Value of $_1$ in eq. VII. 31.
ERR2	-	Value of $_2$ in eq. VII.31.
FLUX(30)	-	Value of the water flux at each node.
GAM(3)	-	Zero-order rate constant of each soil.

TABLE B.1 cont.

HC1 - Hydraulic conductivity of the first node

HCL - Hydraulic conductivity of the last node.

HCOS(3) - Saturated hydraulic conductivity of each soil.

HEDI1 - Value of the pressure head at first node of each element at time

HEDI2 - Value of the pressure head at second node of each element at time

HEDIL(30) - Value of the pressure head at each node at time t.

HEDIN(30) - Value of the pressure head at each node at time .

HEDIX(30) - Value of the pressure head at each node at time .

HEDO - Value of the initial pressure head if it is constant through the soil column.

HL - constant pressure head at the last node if a constant boundary condition is used.

HO - Constant perssure head at surface if a constant boundary condition is used.

I1 - Determines which sorption model is used.
= 1 Linear adsorption isotherm.

I2 - Determines which soil-water characteristics model is used.

= 1 Brooks and Corey
= 2 Van genuchten
= 3 Haverkamp

I3 - Determines which hydraulic conductivity model is used.
= 1 Brooks and Corey
= 2 Van genuchten
= 3 Haverkamp

I4 - If it is equal to one QO (I) = constant.

ICON(30,2)- Relates each node number to its element.

IE - Constant used to indicate if convergence is attained.

IK - Constant used to indicate which soil type applies to each element.

IKK - Constant used to indicate which value of the constant flux at surface is being used

TABLE B.1 cont.

ISA	- Constant used to indicate if the initial concentration is constant over the whole soil profile.
ISP	= 1 equally spaced nodes.
ISS	= 1 Constant initial pressure head.
IST	= 1 Homogeneous soil
ISU	= 1 Transport model is used
ISX	= 1 Mass lumping is used.
JI(3)	- Contains the node number at which each soil type ends.
K1	= 1 Constant concentration at surface.
K2	= 1 Constant flux of concentration at surface at each specified time.
K3	= 1 Free draining profile.
K4	= 1 Constant concentration at last node.
K21	= 1 Constant flux of concentration at surface.
KB1	= 1 Constant flux at surface.
KB2	= 1 Constant flux at last node.
KB3	= 1 Constant pressure head at surface.
KB4	= 1 Constant pressure head at last node.
KB5	= 1 Variable flux at last node.
NELEM	- Number of elements used.
NEWN(2)	- Contains the nodes numbers for each element.
NL	- Number of iterations at each time step.
NNODE	- Number of nodes.
NST	- Maximum number of iterations allowed at each time step.
NT	- Counts number of time steps.
NTM	- Maximum number of time steps allowed.

TABLE B.1 cont.

PF(30)	- Global matrix.
PORO(3)	- Porosity of each soil type.
QL	- Constant flux at last node.
QO(20)	- Values of constant flux at different times at surface.
SCAP1	- Soil water capacity of first node of an element.
SCAP2	- Soil water capacity at second node of an element.
SS(3)	- Specific storage of each soil.
TETIX(30)	- Water content at each node at time .
TETOX(30)	- Water content at each node at time t.
TI	- Time since start of simulation.
TIM	- Value of the time interval at time t.
TIMAX	- Maximum time interval allowed.
TIME	- Total time of simulation.
TIMEX(20)	- Time at which constant flux ends at the surface.
TIMIN	- Minimum time interval allowed.
TIVAL	- Time interval at time t+ t
TORT(3)	- Tortuosity factor of each soil.
XL	- Length of the soil profile.
XLAM	- Decay rate fo the radionuclide under study.
XMG(30,3)	- Global matrix.
W	= 0 explicity algorithm is used. = 1/2 Crank-Nicholson algorithm is used. = 1 Implicit algorithm is used.
Z(30)	- global coordinates of the nodes.

TABLE B.2 - INPUT DATA FOR FLOW EQUATION

CARDS	COLUMNS	FORMAT	VARIABLE
1	1-8	F8.3	XL
	9-16	F8.3	TIME
	17-24	F8.5	TTIVAL
	25-32	F8.3	TIMAX
	33-40	F8.5	TIMIN
	41-48	F8.3	
	49-53	I5	NELEM
	54-58	I5	NTM
	59-63	I5	NST
2	1	I5	ISP
3	1	I5	ISS
4	1	F8.3	HEDO
5	1	I5	IST
6-8	1-8	F8.3	AI(3)
	9-16	F8.3	BI(3)
	17-24	F8.3	CI(3)
	25-32	F8.3	DI(3)
	33-40	F8.3	DI(3)
	41-48	F8.3	HCOS(3)
	49-56	F8.3	PORO(3)
	57-64	E8.3	SS(3)
	65-69	I5	JI(3)
9	1-5	I5	ISU
	6-13	F8.3	ERR1
	14-21	F8.3	ERR2
	22-26	I5	I1
	27-31	I5	I2
	32-36	I5	I3
	36-40	I5	I4
10	1-5	I5	KB1
	6-10	I5	KB2
	11-18	F8.3	QL
	19-23	I5	KB3
	24-28	I5	KB4
	29-35	F8.3	HO
	36-42	F8.3	HL
	43-47	I5	KB5
11	1	F8.3	QOO
12	1	I5	ISX

```
      PROGRAM ODIT(IN,OUT,TAPE5=IN,TAPE6=OUT)
      DIMENSION Z(30),ICON(30,2),HEDIN(30),AI(3),BI(3),CI(3),DI(3),
     1 EI(3),HCOS(3),PORO(3),SS(3),TIMEX(20),QO(20),XSG(30,3),
     2 XMG(30,3),XPG(30),ZE(2),NEWN(2),JI(3),XM(2,2),XS(2,2),
     3 XP(2),TMG(30,3),FPG(30,3),HEDIX(30),HEDIL(30),PF(30),
     4 TETIX(30),HEDIS(30),HEDIP(30)
*     -----READ INPUT VALUES-----
      REWIND 6
      CALL INPU1(XL,TIME,TIVAL,TIMAX,TIMIN,NELEM,W,NNODE,Z,HEDIN,
     1 AI,BI,CI,DI,EI,HCOS,PORO,SS,ISU,I1,I2,I3,ERR1,ERR2,KB1,KB2,
     2 KB3,KB4,KB5,QO,QL,HO,HL,ISX,TIMEX,NTM,NST,JI,ICON)
*     -----DETERMINE IF TRANSPORT EQUATION IS USED----
*     IF(ISU.LT.1)GO TO 2
*     CALL INPU2(
*  2  CONTINUE
      NL=1
      NT=1
      NNN=1
      DO 3 I=1,NNODE
       HEDIP(I)=HEDIN(I)
       HEDIS(I)=HEDIN(I)
   3  HEDIL(I)=HEDIN(I)
      TIM=TIVAL
      IKK=1
      IK=1
      TI=0
      TI=TI+TIVAL
   6  DO 10 I=1,NNODE
      DO 10 J=1,3
      XSG(I,J)=0
      XMG(I,J)=0
  10  XPG(I)=0
*     -----DETERMINE LOCAL MATRICES----
      DO 20 I=1,NELEM
      HEDI1=HEDIN(I)
      HEDI2=HEDIN(I+1)
      DO 15 J=1,2
  15  NEWN(J)=ICON(I,J)
*      WRITE(6,1102)NEWN
*1102  FORMAT(/2I5,'NEW NODE')
      CALL SET(NEWN,ZE,Z,NELEM,ISP,XL)
      CALL ELEM(HEDI1,HEDI2,PORO,SS,ISX,I2,I3,HCOS,AI,BI,CI,DI,EI,
     1 JI,NEWN,IK,ZE,XM,XS,XP,NNODE,HC1,HCL,AL1)
*     -----ASSEMBLE GLOBAL MATRICES----
  20  CALL ASSEM(NEWN,XM,XMG,XS,XSG,XP,XPG)
*     -----INTRODUCE BOUNDARY CONDITIONS-----
      CALL CALC1(TIVAL,HEDIS,XMG,XSG,XPG,NNODE,W,KB1,KB2,KB3,KB4,
     1 KB5,QO,QL,HO,HL,TIMEX,TI,HC1,HCL,AL1,IKK,TMG)
      CALL SOLVE(TMG,XPG,HEDIX,FPG,NNODE)
*     ----CHECK FOR CONVERGENCE----
      CALL ERROR(HEDIX,HEDIL,IE,ERR1,ERR2,NNODE)
*     WRITE(6,111)(HEDIX(I),HEDIL(I),I=1,NNODE)
* 111 FORMAT(3X,F8.3,3X,F8.3)
      IF(NNN.GT.1)GO TO 21
      TI=TIVAL
  21  IF(IE.EQ.0)GO TO 50
      IF(NL.LE.NST)GO TO 25
      TI=TI-.5*TIVAL
      TIVAL=0.5*TIVAL
      IF(TIVAL.LT.TIMIN)GO TO 100
      DO 22 I=1,NNODE
       HEDIN(I)=HEDIS(I)+(TIVAL/(2*TIM))*(HEDIS(I)-HEDIP(I))
```

```
 22     HEDIL(I)=HEDIN(I)
        NL=1
        GO TO 6
 25     DO 30 I=1,NNODE
      HEDIN(I)=0.5*(HEDIX(I)+HEDIS(I))
 30     HEDIL(I)=HEDIX(I)
        NL=NL+1
        GO TO 6
*       ----CONVERGENCE IS ATTAINED----
 50      IF(NNN.GT.1)GO TO 55
         TI=TIVAL
 55     DO 57 I=1,NNODE
        H=ABS(HEDIX(I))
        HH=29.484
        IF(H.GT.HH)GO TO 56
        TETIX(I)=.4531-.02732*LOG(H)
        GO TO 57
 56     TETIX(I)=.6829-.09524*LOG(H)
 57     CONTINUE
        CALL OUT(TI,Z,HEDIX,NT,NL,NNODE,TETIX)
         NNN=NNN+1
        DO 60 I=1,NNODE
        HEDIN(I)=HEDIX(I)+(TIVAL/(2*TIM))*(HEDIX(I)-HEDIS(I))
        HEDIP(I)=HEDIS(I)
        HEDIS(I)=HEDIX(I)
 60     HEDIL(I)=HEDIN(I)
        IF(NL.GT.3)GO TO 70
        TIVAL=1.5*TIVAL
        IF(TIVAL.LE.TIMAX)GO TO 70
        TIVAL=TIMAX
 70     NT=NT+1
        TI=TI+TIVAL
        IF(TI.GT.TIME)GO TO 100
        IF(NT.GT.NTM)GO TO 100
        NL=1
        TIM=TIVAL
        GO TO 6
100     WRITE(6,1001)TI,NT
1001    FORMAT(3X,"PROGRAM TERMINATED WITH TI=",1X,F8.5,2X,"AND NT=",
   1    2X,I5)
        STOP
        END
        SUBROUTINE INPU1(XL,TIME,TIVAL,TIMAX,TIMIN,NELEM,W,NNODE,Z,
   1    HEDIN,AI,BI,CI,DI,EI,HCOS,PORO,SS,ISU,I1,I2,I3,ERR1,ERR2,
   2    KB1,KB2,KB3,KB4,KB5,QO,QL,HO,HL,ISX,TIMEX,NTM,NST,JI,ICON)
        DIMENSION Z(30),HCOS(3),PORO(3),SS(3),TIMEX(20),QO(20),JI(3),
   1    ICON(30,2),HEDIN(30),AI(3),BI(3),CI(3),DI(3),EI(3)
        WRITE(6,1000)
        READ(5,1010)XL,TIME,TIVAL,TIMAX,TIMIN,W,NELEM,NTM,NST
        WRITE(6,1020)XL,TIME,TIVAL,TIMAX,TIMIN,W,NELEM,NTM,NST
        NNODE=NELEM+1
*       ----DETERMINE GLOBAL COORDINATES OF THE NODES----
        READ(5,1030)ISP
        DO 1 I=1,NNODE
  1     Z(I)=0
        IF(ISP.LT.1)GO TO 5
        DO 2 I=1,NNODE
        Z(I)=(I-1)*XL/NELEM
  2     WRITE(6,1040)I,Z(I)
        GO TO 10
  5     DO 7 I=1,NNODE
        READ(5,1050)Z(I)
  7     WRITE(6,1040)I,Z(I)
```

```
 10     DO 12 I=1,NELEM
        DO 12 J=1,2
  12    ICON(I,J)=I+J-1
*       ----OBTAIN INITIAL PRESSURE HEADS----
        READ(5,1030)ISS
        IF(ISS.LT.1)GO TO 17
        READ(5,1050)HEDO
        WRITE(6,1070)HEDO
*       DO 15 I=1,NNODE
        DO 15 I=1,12
        XX=.15+.000833*(I-1)*5/1
        XXX=(.6829-XX)/.09524
        HEDIN(I)=-EXP(XXX)
  15    WRITE(6,1040)I,HEDIN(I)
        DO 16 I=13,26
      HEDIN(I)=HEDO
  16    WRITE(6,1040)I,HEDIN(I)
* 15    HEDIN(I)=HEDO
        GO TO 20
  17    DO 18 I=1,NNODE
        READ(5,1050)HEDIN(I)
  18    WRITE(6,1040)I,HEDIN(I)
  20    READ(5,1030)IST
        IF(IST.LT.1)GO TO 25
        READ(5,1090)AII,BII,CII,DII,EII,HCOSI,POROI,SSI,JII
        WRITE(6,1100)AII,BII,CII,DII,EII,HCOSI,POROI,SSI,JII
        DO 22 I=1,3
        AI(I)=AII
        BI(I)=BII
        CI(I)=CII
        DI(I)=DII
        EI(I)=EII
        HCOS(I)=HCOSI
        PORO(I)=POROI
        JI(I)=JII
  22    SS(I)=SSI
        GO TO 30
  25    DO 28 I=1,3
        READ(5,1090)AI(I),BI(I),CI(I),DI(I),EI(I),HCOS(I),PORO(I),
     1  SS(I),JI(I)
  28    WRITE(6,1100)AI(I),BI(I),CI(I),DI(I),EI(I),HCOS(I),PORO(I),
     1  SS(I),JI(I)
  30    CONTINUE
*       ----DETERMINE IF TRANSPORT MODEL IS USED----
        READ(5,1105)ISU,ERR1,ERR2,I1,I2,I3,I4
*       ----OBTAIN BOUNDARY CONDITIONS----
        READ(5,1110)KB1,KB2,QL,KB3,KB4,HO,HL,KB5
        IF(KB3.LT.1)GO TO 31
        HEDIN(1)=HO
  31    IF(KB4.LT.1)GO TO 315
        HEDIN(NNODE)=HL
*       HEDIN(NNODE)=HL
*       IF(I4.LT.1)GO TO 32
 315    READ(5,1050)QQQ
         DO 316 I=1,20
         TIMEX(I)=TIME
 316     QQ(I)=0.
*       QQ(1)=0.
*       TIMEX(1)=TIME/2.
*       QQ(2)=QQQ
*       TIMEX(2)=TIME
        GO TO 40
  32    DO 35 I=1,20
```

```
      READ(5,1120)TIMEX(I),QO(I)
 35   WRITE(6,1130)TIMEX(I),QO(I)
*     ----DETERMINE IF MASS LUMPING IS USED----
 40   READ(5,1030)ISX
*     ----
 1000 FORMAT(//,7X,"UNSATURATED FLOW AND TRANSPORT",/)
 1010 FORMAT(2F8.3,F8.5,F8.3,F8.5,F8.3,3I5)
 1020 FORMAT(3X,"XL=",F8.3,3X,"TIME=",F8.3,3X,"TIVAL=",E8.3,3X,
     1 "TIMAX=",F8.3,/,3X,"TIMIN=",E8.3,3X,"W=",F8.3,3X,"NELEM=",
     2 I5,3X,"NTM=",I5,3X,"NST=",I5)
 1030 FORMAT(I5)
 1040 FORMAT(4X,I4,6X,F8.3)
 1050 FORMAT(F8.3)
 1070 FORMAT(/,4X,"HEDO=",F8.3)
 1090 FORMAT(7F8.3,E8.3,I5)

 1100 FORMAT(3X,7(3X,F8.3),3X,E8.3,3X,I5)
 1105 FORMAT(I5,2F8.3,4I5)
 1110 FORMAT(2I5,F8.3,2I5,2F8.3,I5)
 1120 FORMAT(2F8.3)
 1130 FORMAT(3X,F8.3,3X,F8.3)
      RETURN
      END
      SUBROUTINE SET(NEWN,ZE,Z,NELEM,ISP,XL)
      DIMENSION Z(30),ZE(2),NEWN(2)
      IF(ISP.LT.1)GO TO 1
      ZE(1)=0
      ZE(2)=XL/NELEM
      GO TO 5
  1   J=NEWN(1)
      JJ=NEWN(2)
      ZE(1)=0
      ZE(2)=Z(JJ)-Z(J)
  5   RETURN
      END
      SUBROUTINE ELEM(HEDI1,HEDI2,PORO,SS,ISX,I2,I3,HCOS,AI,BI,
     1 CI,DI,EI,JI,NEWN,IK,ZE,XM,XS,XP,NNODE,HC1,HCL,AL1)
      DIMENSION PORO(3),SS(3),HCOS(3),AI(3),BI(3),CI(3),DI(3),
     1 EI(3),JI(3),NEWN(2),ZE(2),XM(2,2),XS(2,2),XP(2)
      IAS=NEWN(1)
      IASS=JI(IK)
      IF(IAS.LT.IASS)GO TO 5
      IK=IK+1
  5   AL=ZE(2)-ZE(1)
      CALL HCWC(HCO1,HCO2,TETI1,TETI2,SCAP1,SCAP2,HEDI1,HEDI2,
     1 I2,I3,IK,PORO,HCOS,AI,BI,CI,DI,EI,IAS)
      IF(ISX.EQ.1)GO TO 10
      XM(1,1)=(AL/12)*(3*(TETI1*SS(IK)/PORO(IK)+SCAP1)+(TETI2*SS(IK)
     1 /PORO(IK)+SCAP2))
      XM(1,2)=(AL/12)*(TETI1*SS(IK)/PORO(IK)+SCAP1+TETI2*SS(IK)/
     1 PORO(IK)+SCAP2)
      XM(2,1)=XM(1,2)
      XM(2,2)=(AL/12)*(3*(TETI2*SS(IK)/PORO(IK)+SCAP2)+(TETI1*SS(IK)
     1 /PORO(IK)+SCAP1))
      GO TO 15
 10   XM(1,1)=(AL/6)*(2*(TETI1*SS(IK)/PORO(IK)+SCAP1)+(TETI2*SS(IK)
     1 /PORO(IK)+SCAP2))
      XM(1,2)=0
      XM(2,1)=0
      XM(2,2)=(AL/6)*(2*(TETI2*SS(IK)/PORO(IK)+SCAP2)+(TETI1*SS(IK)
     1 /PORO(IK)+SCAP1))
 15   XS(1,1)=(1/(2*AL))*(HCO1+HCO2)
      XS(1,2)=-XS(1,1)
```

```
      XS(2,1)=XS(1,2)
      XS(2,2)=XS(1,1)
      XP(1)=0.5*(HC01-HC02)
      XP(2)=XP(1)
      IF(IAS.GT.1)GO TO 30
      HC1=HC01
* 30  DO 22 I=1,2
*     DO 22 J=1,2
* 22  WRITE(6,112)XM(I,J),XS(I,J),XP(I)
*112  FORMAT(3X,3(E9.3,3X))
*     WRITE(6,111)HC1
*111  FORMAT(/,3X,"HC1 =",F8.3)
  30  IASL=NEWN(2)
      IF(IASL.LT.NNODE)GO TO 40
      AL1=AL
      HCL=HC02
  40  RETURN
      END
      SUBROUTINE HCWC(HC01,HC02,TETI1,TETI2,SCAP1,SCAP2,HEDI1,
     1 HEDI2,I2,I3,IK,PORO,HC0S,AI,BI,CI,DI,EI,IAS)
      DIMENSION PORO(3),HC0S(3),AI(3),BI(3),CI(3),DI(3),EI(3)
*    1 TETIX(30)
*     ----DETERMINE WHICH WATER CONTENT MODEL APPLIES----
*     ----BROOKS AND COREY MODEL----
      HED11=ABS(HEDI1)
      HED22=ABS(HEDI2)
      IF(I2.GT.1)GO TO 10
      XP=CI(IK)
      TETI1=AI(IK)+((PORO(IK)-AI(IK))*(BI(IK)/HED11)**XP)
      TETI2=AI(IK)+((PORO(IK)-AI(IK))*(BI(IK)/HED22)**XP)
      XPPP=1/XP
      XPP=(XP+1)/XP
      SCAP1=(XP/(BI(IK)*(PORO(IK)-AI(IK))**XPPP*(TETI1-AI(IK))**XPP))
      SCAP2=(XP/(BI(IK)*(PORO(IK)-AI(IK))**XPPP*(TETI2-AI(IK))**XPP))
      GO TO 50
*     -----VAN GENUCHTEN MODEL-----
  10  IF(I2.GT.2)GO TO 20
      XP=CI(IK)
      XPP=1-1/XP
      XP1=XP-1
      XPP1=XPP+1
     TETI1=(PORO(IK)-AI(IK))*((1/(1+(BI(IK)*HED11)**XP))**XPP)+AI(IK)
     TETI2=(PORO(IK)-AI(IK))*((1/(1+(BI(IK)*HED11)**XP))**XPP)+AI(IK)
      SCAP1=XPP*(PORO(IK)-AI(IK))*((1/(1+(BI(IK)*HED11)**XP))**XPP1)*
     1 XP*(BI(IK)**XP)*(HED11**XP1)
      SCAP2=XPP*(PORO(IK)-AI(IK))*((1/(1+(BI(IK)*HED22)**XP))**XPP1)*
     1 XP*(BI(IK)**XP)*(HED22**XP1)
      GO TO 50
*     ----HAVERKAMP MODEL----
  20  IF(I2.GT.3)GO TO 30
      XP=CI(IK)
      XPP=XP-1
      TETI1=BI(IK)*(PORO(IK)-AI(IK))/(BI(IK)+HED11**XP)+AI(IK)
      TETI2=BI(IK)*(PORO(IK)-AI(IK))/(BI(IK)+HED22**XP)+AI(IK)
      SCAP1=BI(IK)*XP*(PORO(IK)-AI(IK))*(1/(BI(IK)+HED11**XP)**2)*
     1 HED11**XPP
      SCAP2=XP*BI(IK)*(PORO(IK)-AI(IK))*(1/(BI(IK)+HED22**XP)**2)*
     1 HED22**XPP
*     ----DETERMINE WHICH HYDRAULIC CONDUCTIVITY MODEL APPLIES----
*     -----WARRICK MODEL-----
  30  IF(I2.GT.4)GO TO 50
      XP=-29.484
      XPP=-14.495
```

```
      IF(HEDI1.GT.XP)GO TO 32
      TETI1=.6829-.09524*LOG(HED11)
      HCO1=1934000/(HED11)**3.4095
      SCAP1=-.09524/HEDI1
      GO TO 34
32    TETI1=.4531-.02732*LOG(HED11)
      HCO1=516.8/(HED11)**0.97814
      SCAP1=-.02732/HEDI1
34    IF(HEDI2.GT.XP)GO TO 36
      TETI2=.6829-.09524*LOG(HED22)
      HCO2=1934000/(HED22)**3.4095
      SCAP2=-.09524/HEDI2
      GO TO 100
36    TETI2=.4531-.02732*LOG(HED22)
      HCO2=516.8/(HED22)**.97814
      SCAP2=-.02732/HEDI2
      GO TO 100
*     ----BROOKS AND COREY MODEL----
50    IF(I3.GT.1)GO TO 60
      XP=(2+3*CI(IK))/CI(IK)
      HCO1=HCOS(IK)*((TETI1-AI(IK))/(PORO(IK)-AI(IK)))**XP
      HCO2=HCOS(IK)*((TETI2-AI(IK))/(PORO(IK)-AI(IK)))**XP
      GO TO 100
*     ----VAN GENUCHTEN MODEL----
60    IF(I3.GT.2)GO TO 70
      XP=1-1/CI(IK)
      XPP=1/XP
      HCO1=HCOS(IK)*((TETI1-AI(IK))/(PORO(IK)-AI(IK)))**0.5*(1-(1-((
     1    TETI1-AI(IK))/(PORO(IK)-AI(IK)))**XPP)**XP)**2
      HCO2=HCOS(IK)*((TETI2-AI(IK))/(PORO(IK)-AI(IK)))**0.5*(1-(1-((
     1    TETI2-AI(IK))/(PORO(IK)-AI(IK)))**XPP)**XP)**2
      GO TO 100
*     ----HAVERKAMP MODEL----
70    IF(I3.GT.3)GO TO 100
      XP=EI(IK)
      HCO1=HCOS(IK)*(DI(IK)/(DI(IK)+HED11**XP))

      HCO2=HCOS(IK)*(DI(IK)/(DI(IK)+HED22**XP))
100   IF(HEDI1.LE.0)GO TO 150
      TETI1=PORO(IK)
      SCAP1=0
      HCO1=HCOS(IK)
150   IF(HEDI2.LE.0)GO TO 200
      TETI2=PORO(IK)
      SCAP2=0
      HCO2=HCOS(IK)
* 200 TETIX(IAS)=TETI1
*     IF(IAS.LT.25)GO TO 300
*     IIAS=IAS+1
*     TETIX(IIAS)=TETI2
* 200 WRITE(6,101)TETI1,TETI2,HCO1,HCO2,SCAP1,SCAP2
*101  FORMAT(3X,6(E9.3,2X))
200   RETURN
      END
      SUBROUTINE ASSEM(NEWN,XM,XMG,XS,XSG,XP,XPG)
     DIMENSION NEWN(2),XM(2,2),XMG(30,3),XS(2,2),XSG(30,3),
     1    XP(2),XPG(30)
      IUBW=2
      DO 11 I=1,2
      DO 10 J=1,2
      II=NEWN(I)
      JJ=NEWN(J)
     KK=IUBW+JJ-II
```

```
          XMG(II,KK)=XMG(II,KK)+XM(I,J)
   10     XSG(II,KK)=XSG(II,KK)+XS(I,J)
   11    XPG(II)=XPG(II)+XP(I)
*  10    WRITE(6,15)(XMG(II,KK),XSG(II,KK),XPG(II),I=1,NNODE)
*  15    FORMAT(3X,3(E8.3,3X))
          RETURN
          END
          SUBROUTINE CALC1(TIVAL,HEDIS,XMG,XSG,XPG,NNODE,W,KB1,KB2,KB3,
      1   KB4,KB5,QO,QL,HO,HL,TIMEX,TI,HC1,HCL,AL1,IKK,TMG)
          DIMENSION HEDIS(30),XMG(30,3),XSG(30,3),XPG(30),TMG(30,3),
      1   FPG(30,3),TIMEX(20),QO(20)
          DO 1 I=1,NNODE
          DO 1 J=1,3
          TMG(I,J)=0
   1      FPG(I,J)=0
*         ----DETERMINE IF NEUMANN VARIABLE FLUX APPLIES----
          IF(KB5.LT.1)GO TO 5
          AAL=HCL/AL1
          GO TO 7
   5      AAL=0
   7      DO 10 I=1,NNODE
          DO 10 J=1,3
          TMG(I,J)=XMG(I,J)/TIVAL+W*XSG(I,J)
   10     FPG(I,J)=XMG(I,J)/TIVAL+(W-1)*XSG(I,J)
          TMG(NNODE,1)=TMG(NNODE,1)-W*AAL
          TMG(NNODE,2)=TMG(NNODE,2)+W*AAL
          FPG(NNODE,1)=FPG(NNODE,1)-(W-1)*AAL
          FPG(NNODE,2)=FPG(NNODE,2)+(W-1)*AAL
          DO 15 I=1,NNODE
          DO 15 J=1,3
   15     XMG(I,J)=0
          DO 20 J=2,3
          L=J-1
   20     XMG(1,1)=XMG(1,1)+FPG(1,J)*HEDIS(L)
          II=NNODE-1
          DO 25 I=2,II
          DO 25 J=1,3
          K=I+J-2
   25     XMG(I,1)=XMG(I,1)+FPG(I,J)*HEDIS(K)
          DO 30 J=1,2
          L=NNODE-2+J
   30     XMG(NNODE,1)=XMG(NNODE,1)+FPG(NNODE,J)*HEDIS(L)
*         ----DETERMINE IF CONSTANT FLUX APPLIES----
          TTT=TIMEX(IKK)
          IF(TI.LT.TTT)GO TO 35
          IKK=IKK+1
   35     QQ1=QO(IKK)-HC1
          QQ2=HCL-QL
          IF(KB1.EQ.1)GO TO 40
          QO(IKK)=0
   40     IF(KB2.EQ.1)GO TO 45
          QL=00
   45     XPG(1)=XPG(1)+XMG(1,1)+QQ1
          L=NNODE-1
          DO 50 I=2,L
   50     XPG(I)=XPG(I)+XMG(I,1)
          XPG(NNODE)=XPG(NNODE)+XMG(NNODE,1)+QQ2
*         -----DETERMINE IF CONSTANT HYDRAULIC HEAD APPLIES-----
          IF(KB3.LT.1)GO TO 60
          TMG(1,2)=1
          TMG(1,3)=0
          XPG(2)=XPG(2)-HO*TMG(2,1)
          XPG(1)=HO
```

```
      TMG(2,1)=0
 60   IF(KB4.LT.1)GO TO 70
      NN=NNODE-1
      XPG(NNODE)=HL
      XPG(NN)=XPG(NN)-HL*TMG(NN,3)
      TMG(NNODE,1)=0
      TMG(NNODE,2)=1
      TMG(NN,3)=0
 70   CONTINUE
*     DO 100 I=1,NNODE
*     DO 100 J=1,3
* 100 WRITE(6,110)FPG(I,J),TMG(I,J),XPG(I)
* 110 FORMAT(3X,3(E9.3,3X))
      RETURN
      END
      SUBROUTINE SOLVE(TMG,XPG,HEDIX,FPG,NNODE)
      DIMENSION TMG(30,3),XPG(30),HEDIX(30),FPG(30,3)
      DO 5 I=1,NNODE
      DO 5 J=1,3
 5    FPG(I,J)=0
      FPG(1,1)=TMG(1,2)
      FPG(1,2)=TMG(1,3)/FPG(1,1)
      FPG(1,3)=XPG(1)/FPG(1,1)
      DO 10 I=2,NNODE
      II=I-1
      FPG(I,1)=TMG(I,2)-TMG(I,1)*FPG(II,2)
      FPG(I,2)=TMG(I,3)/FPG(I,1)
 10   FPG(I,3)=(XPG(I)-TMG(I,1)*FPG(II,3))/FPG(I,1)
      HEDIX(NNODE)=FPG(NNODE,3)
      NI=NNODE-1
      DO 20 I=1,NI
      II=NNODE-I
      III=II+1
 20   HEDIX(II)=FPG(II,3)-FPG(II,2)*HEDIX(III)
*    DO 50 I=1,NNODE
*    DO 50 J=1,3
* 50 WRITE(6,110)FPG(I,J),HEDIX(I)
* 110  FORMAT(3X,2(E9.3,3X))
      RETURN
      END
      SUBROUTINE ERROR(HEDIX,HEDIL,IE,ERR1,ERR2,NNODE)
      DIMENSION HEDIX(30),HEDIL(30)
      DO 5 I=1,NNODE
      TTT=ABS(HEDIX(I)-HEDIL(I))
      TTTT=ERR2*HEDIX(I)
      TT=ERR1+ABS(TTTT)
      IF(TTT.GT.TT)GO TO 10
 5    CONTINUE
      IE=0
      GO TO 15
 10   IE=1
 15   RETURN
      END
      SUBROUTINE OUT(TI,Z,HEDIX,NT,NL,NNODE,TETIX)
      DIMENSION Z(30),HEDIX(30),TETIX(30)
*     DO 11 I=1,NNODE
*     H=-HEDIX(I)
*     HH=29.484
*     WRITE(6,111)
*111  FORMAT("GO")
*     IF(H.GT.HH)GO TO 6
*     TETIX(I)=.4531-.02732*LOG(H)
*     GO TO 11
```

```
*  6        TETLA(L)=.0524*.0VOL**LL(Y)
*  11        CONTINUE
            WRITE(6,20)TI,NL,NT
            WRITE(6,150)
            WRITE(6,200)(I,Z(I),HED1X(I),TETIX(I),I=1,NNODE)
   20        FORMAT(//,10X,"TIME= ",1X,F8.5,4X,"NL= ",I5,4X,"NT= ",I5)
   150       FORMAT(/,4X,"NNODE",8X,"COORDINATE",7X,"PRESSURE HEAD",
      1      7X,"WATER CONTENT")
   200       FORMAT(4X,I4,9X,F8.3,10X,F8.3,10X,F8.3)
             RETURN
             END
--EOR--
    125.     .40      .0100    .1       .00001  1.0      25    015  10
    1
    1
    -159.19
    1
    .0       00.      0.       0.       0.       00.      .4       .400E-0726
    0     .50     .001     0     4     1     0
    0     0     0.       1     1     -14.495 -159.19 0
    0.00
    00
--EOR--
```

UNSATURATED FLOW AND TRANSPORT

```
XL= 125.000    TIME=     .400    TIVAL=.100E-01    TIMAX=     .100
TIMIN=.100E-04    W=   1.000    NELEM=    25    NTM=    15    NST=    10
      1         .000
      2        5.000
      3       10.000
      4       15.000
      5       20.000
      6       25.000
      7       30.000
      8       35.000
      9       40.000
     10       45.000
     11       50.000
     12       55.000
     13       60.000
     14       65.000
     15       70.000
     16       75.000
     17       80.000
     18       85.000
     19       90.000
     20       95.000
     21      100.000
     22      105.000
     23      110.000
     24      115.000
     25      120.000
     26      125.000

 HEDO=-159.190
      1     -269.169
      2     -257.651
      3     -246.626
      4     -236.074
      5     -225.972
      6     -216.303
```